Indirect Probes of the Dark Sector

Michele Papucci
IAS

P.Meade, M.P., T.Volansky 0901.2925
P.Meade, M.P., A.Strumia, T.Volansky 0905.0480
M.P., A.Strumia 0912.0742
P.Meade, S.Nussinov, M.P., T.Volansky 0910.4160

LBNL Rpm, Feb. 16th 2010

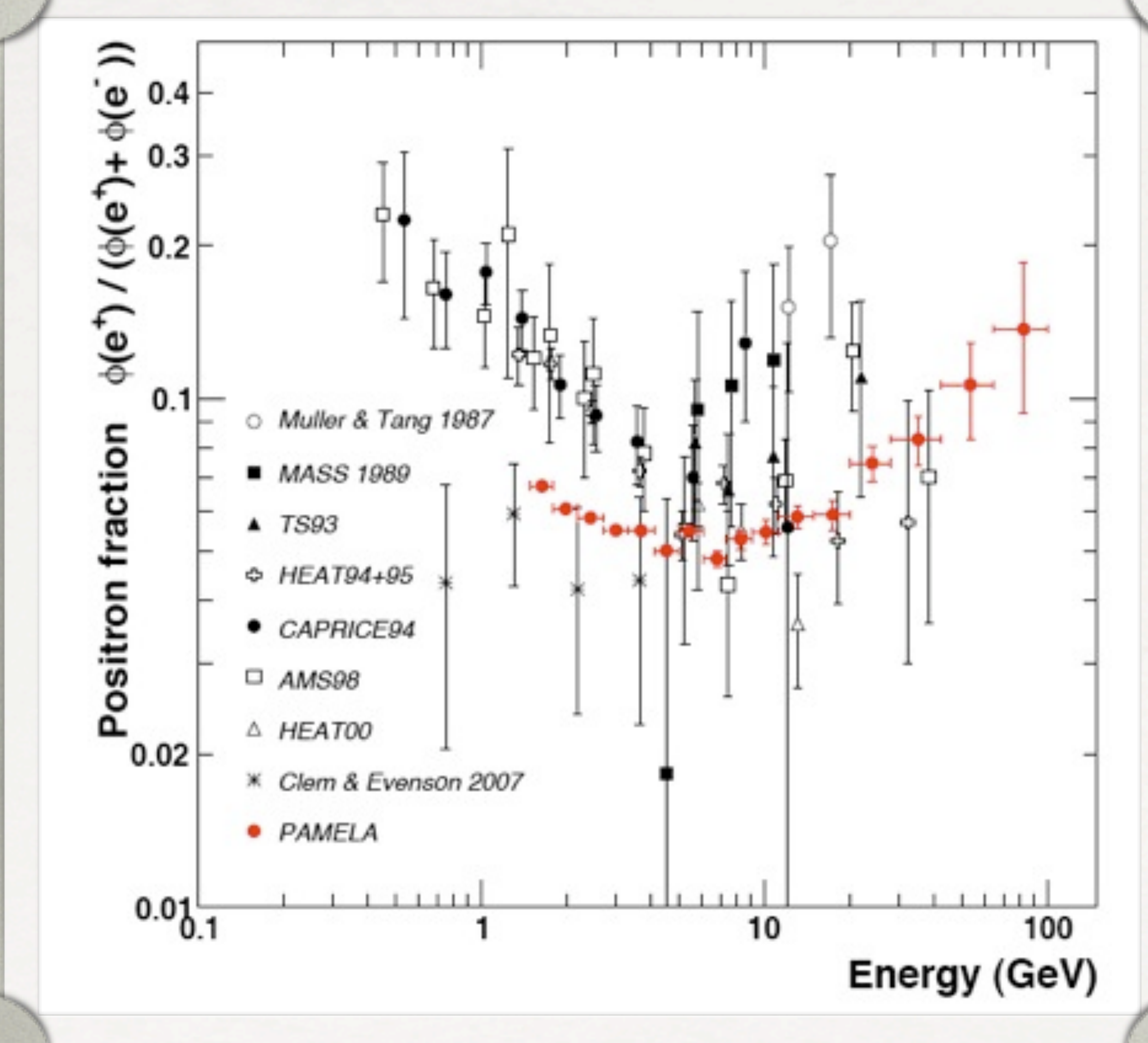
Outline

- Review of PAMELA, Fermi and all that
- Dark Matter explanations (model independent analysis)
  - Which models fit the data?
  - Which models survive the γ constraints?
- Other probes of hidden sectors
- Conclusions

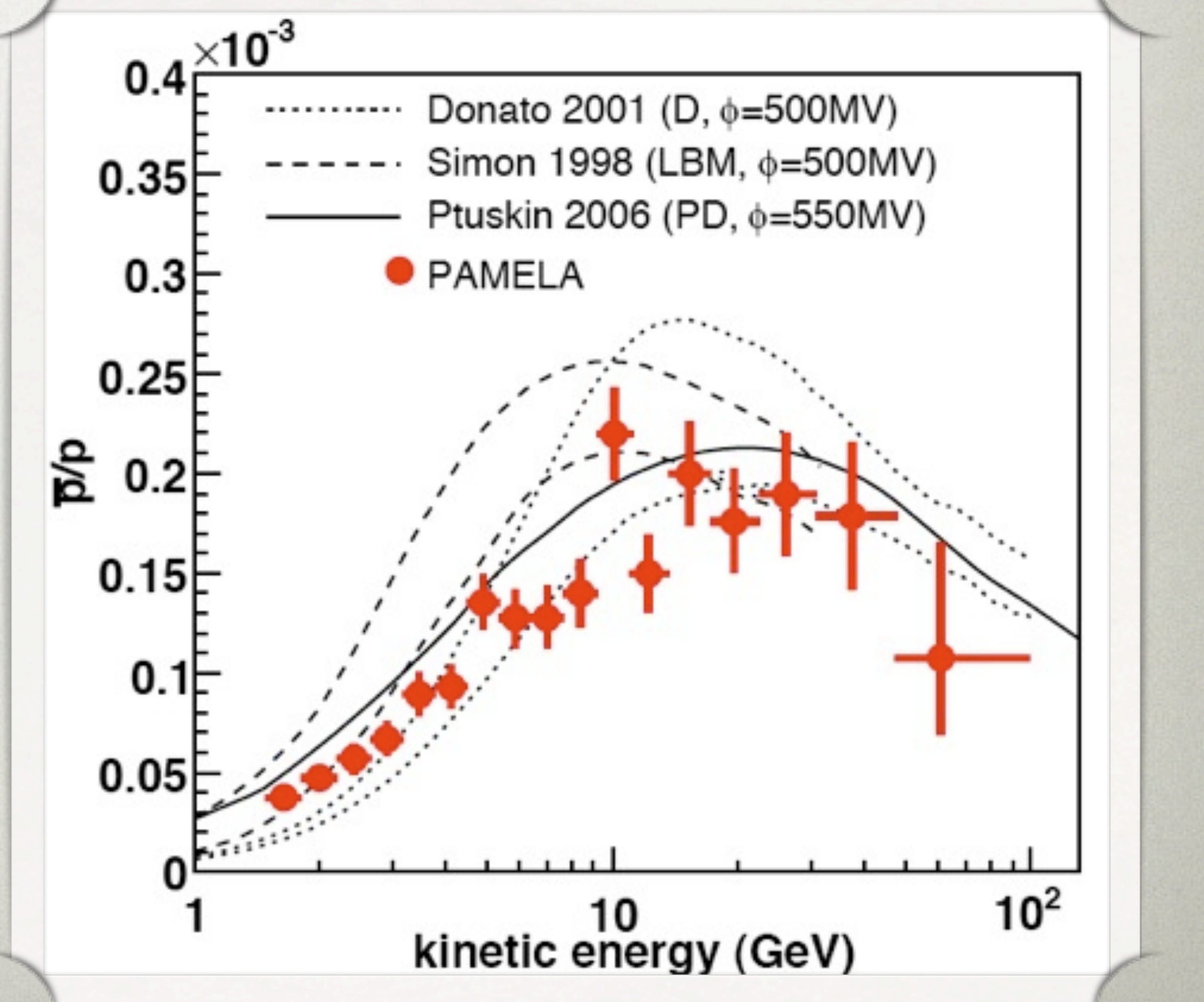
Cosmic Rays News

PAMELA results

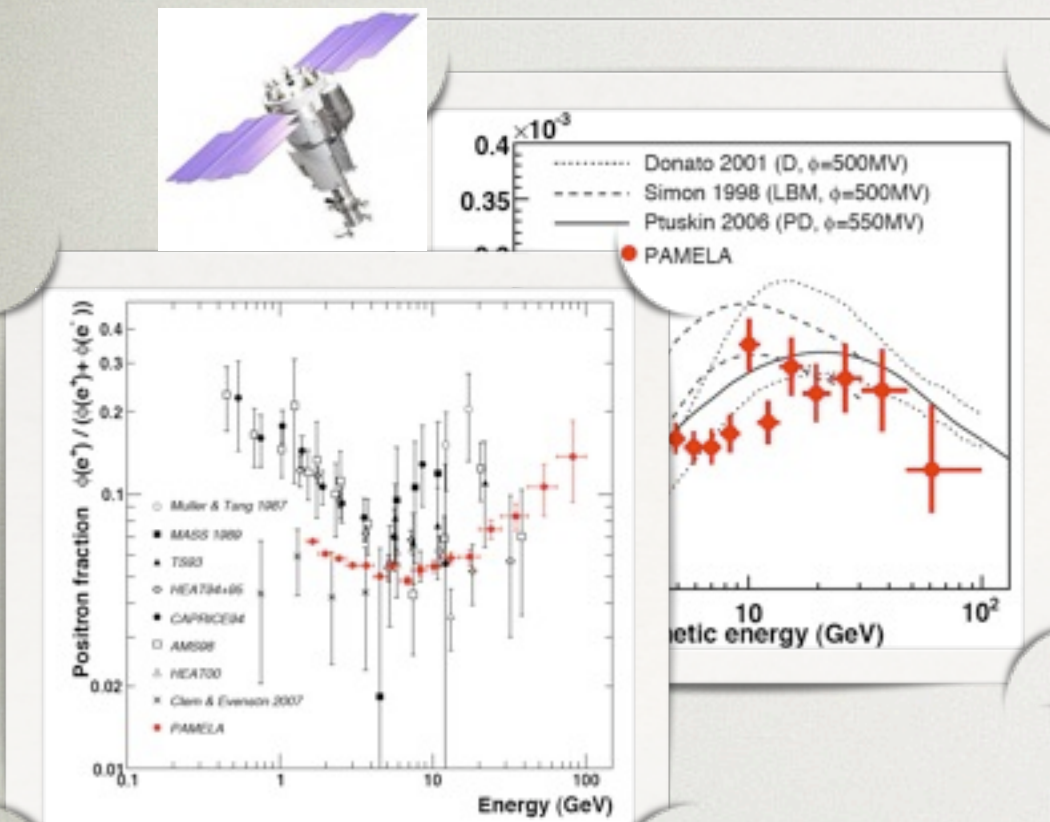
Positron fraction



Antiproton/ proton ratio



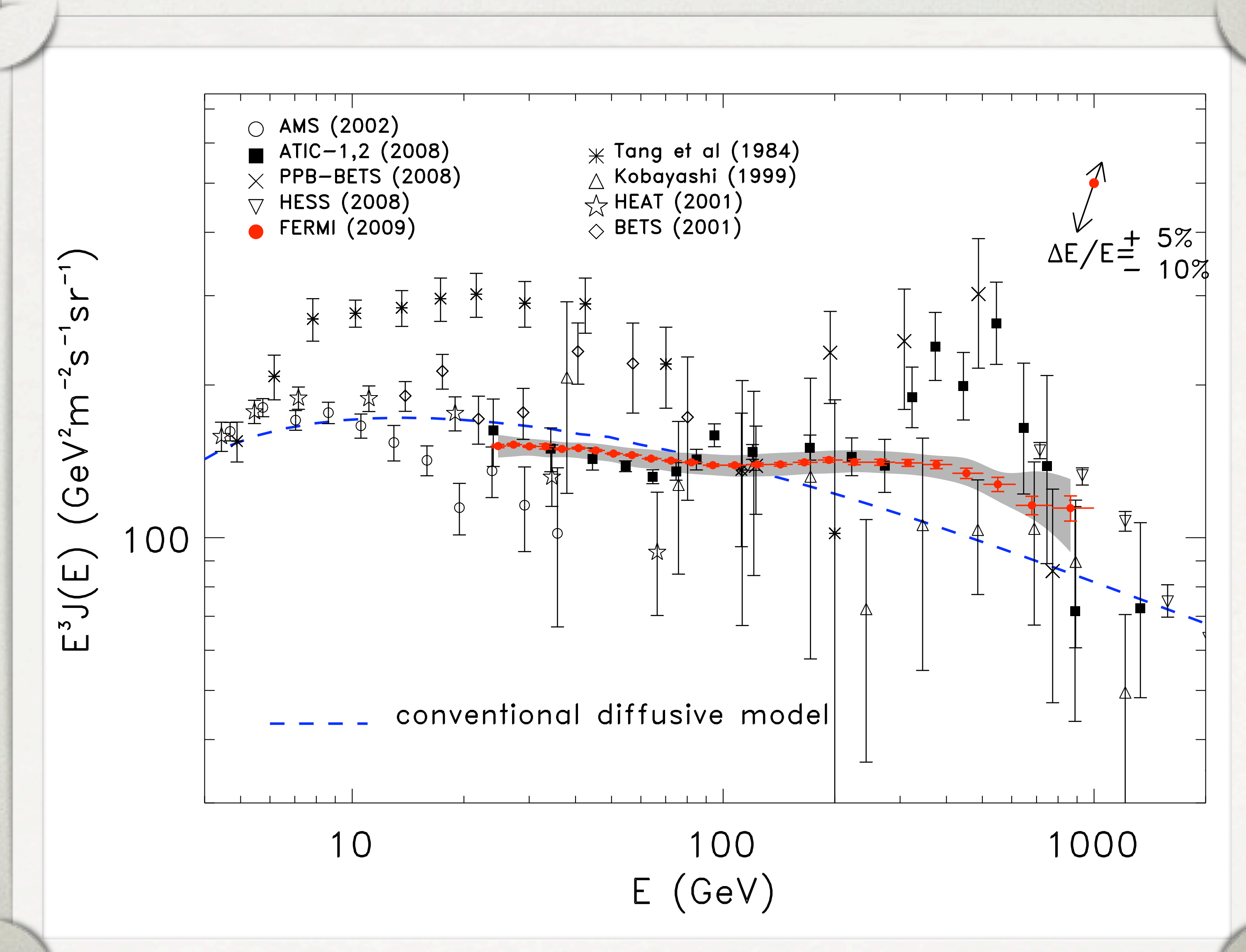
Cosmic Rays News



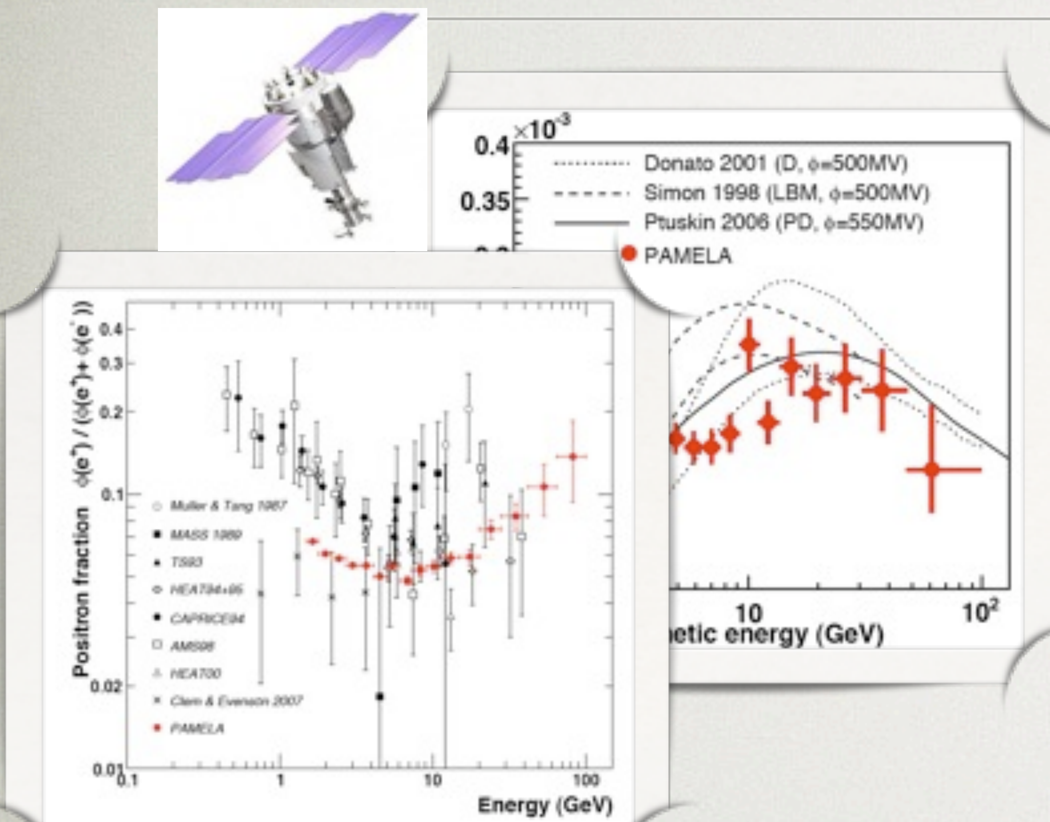
PAMELA results

Fermi results

Electron + Positron Flux

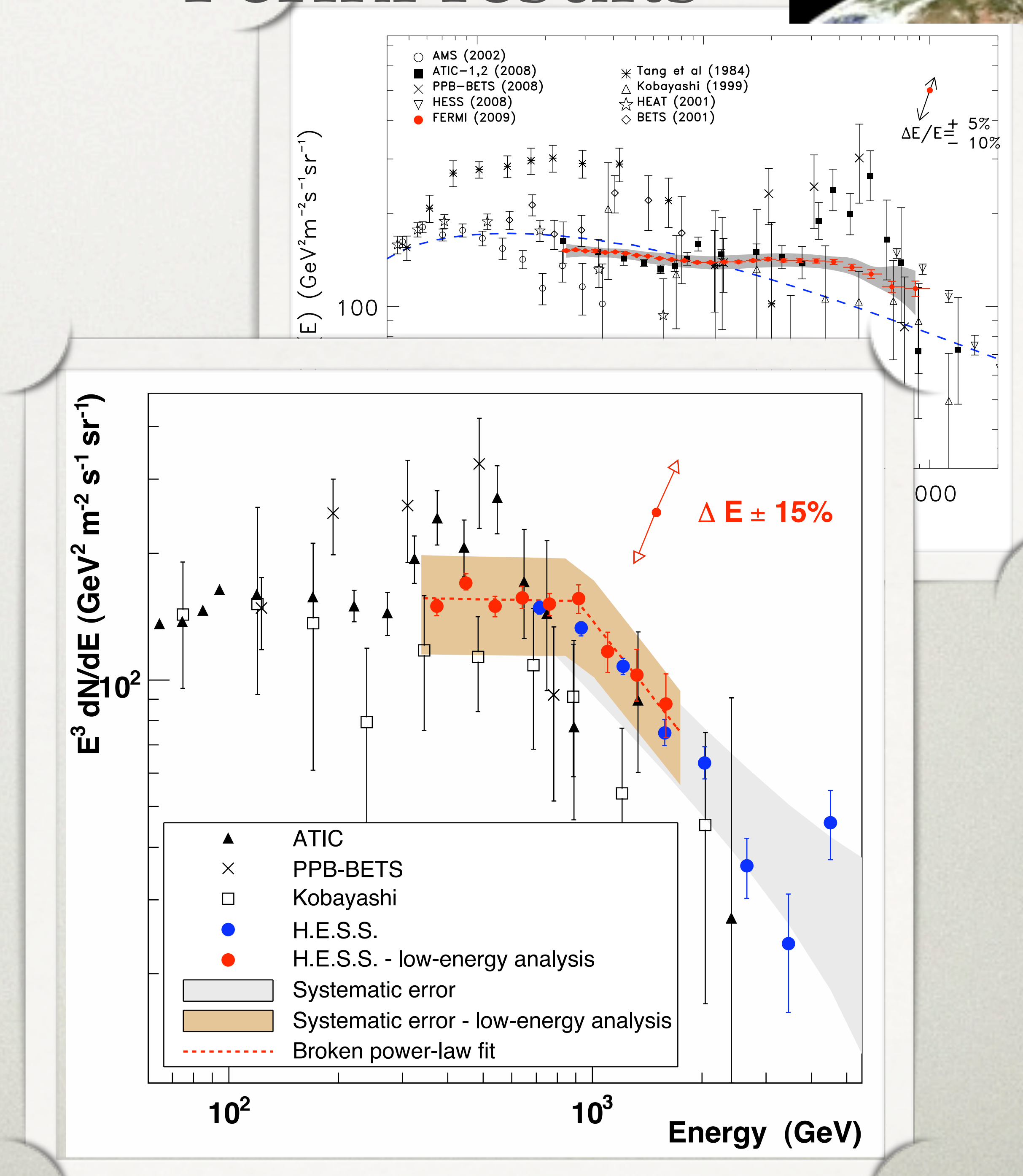


Cosmic Rays News



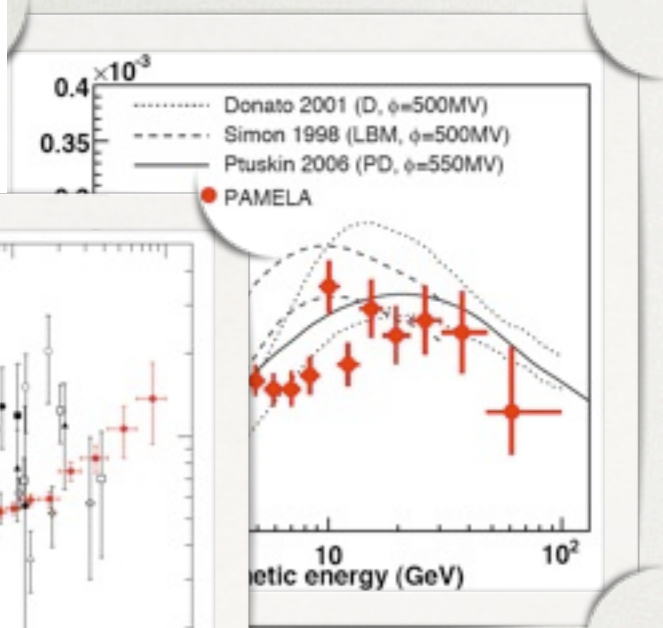
PAMELA results

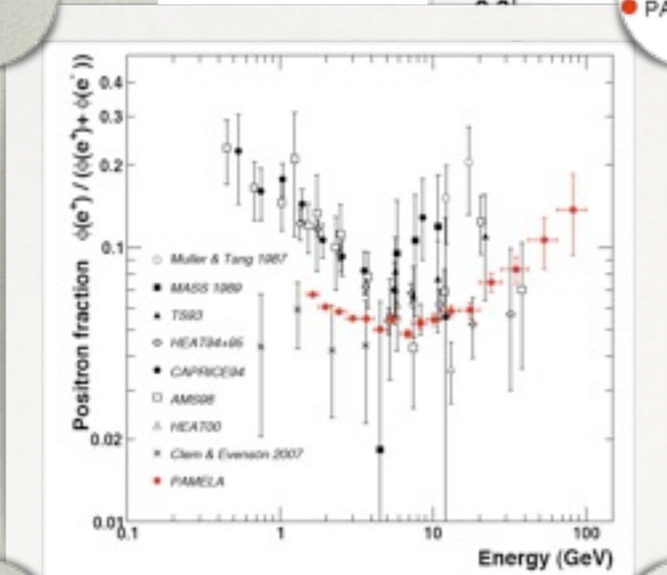
Fermi results



HESS results

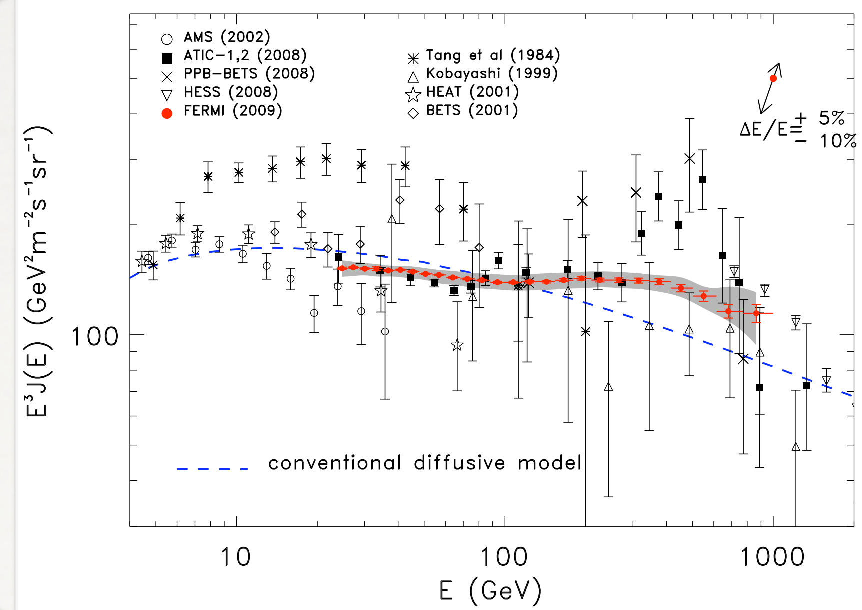
Cosmic Rays News



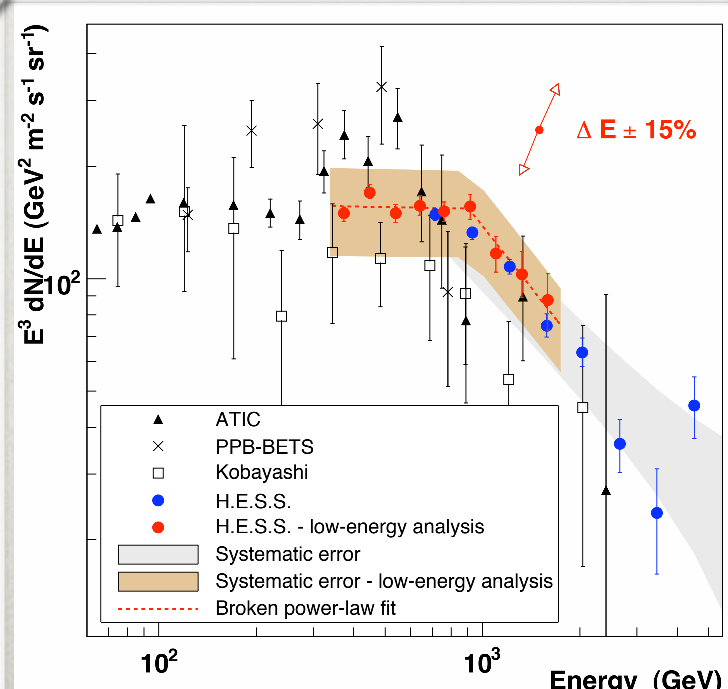


PAMELA results

Fermi results

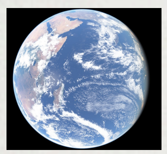


HESS results



Is there a “PAMELA anomaly”?

Cosmic Rays Propagation 101

Earth 

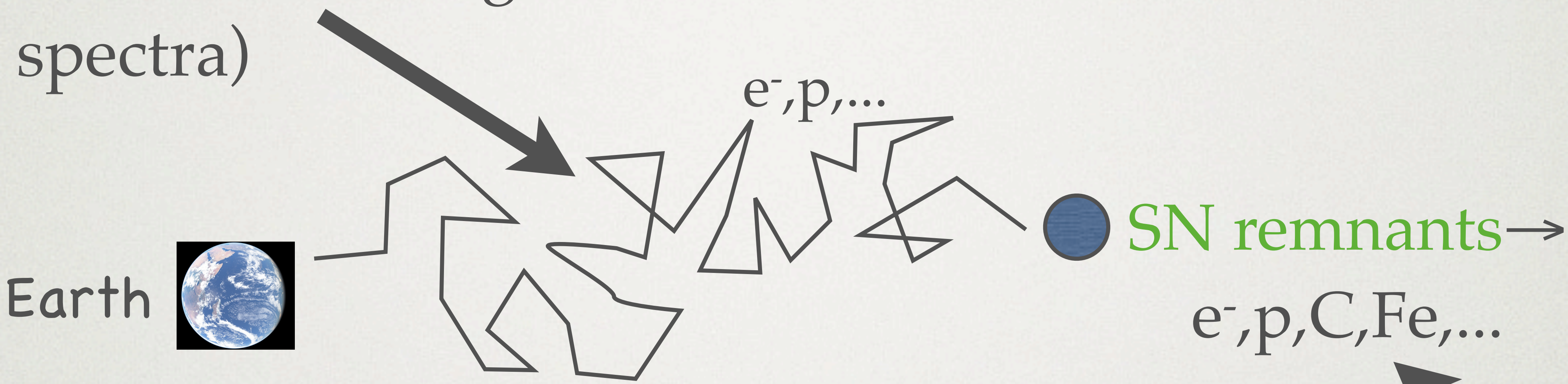
SN remnants→

e^-,p,C,Fe,...

Primary CRs

Cosmic Rays Propagation 101

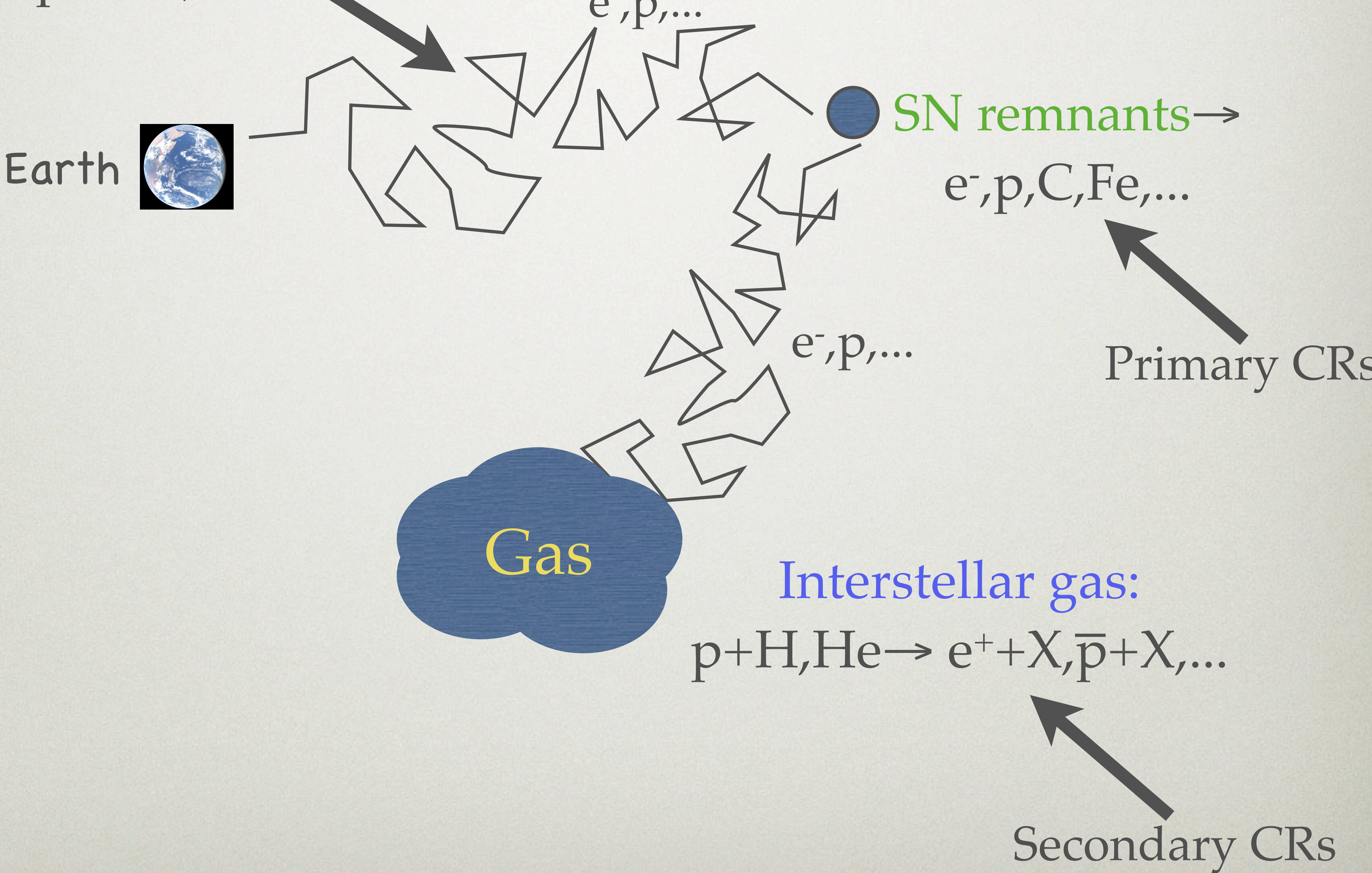
Diffusion on turbulent galactic B field
(soften spectra)



Primary CRs

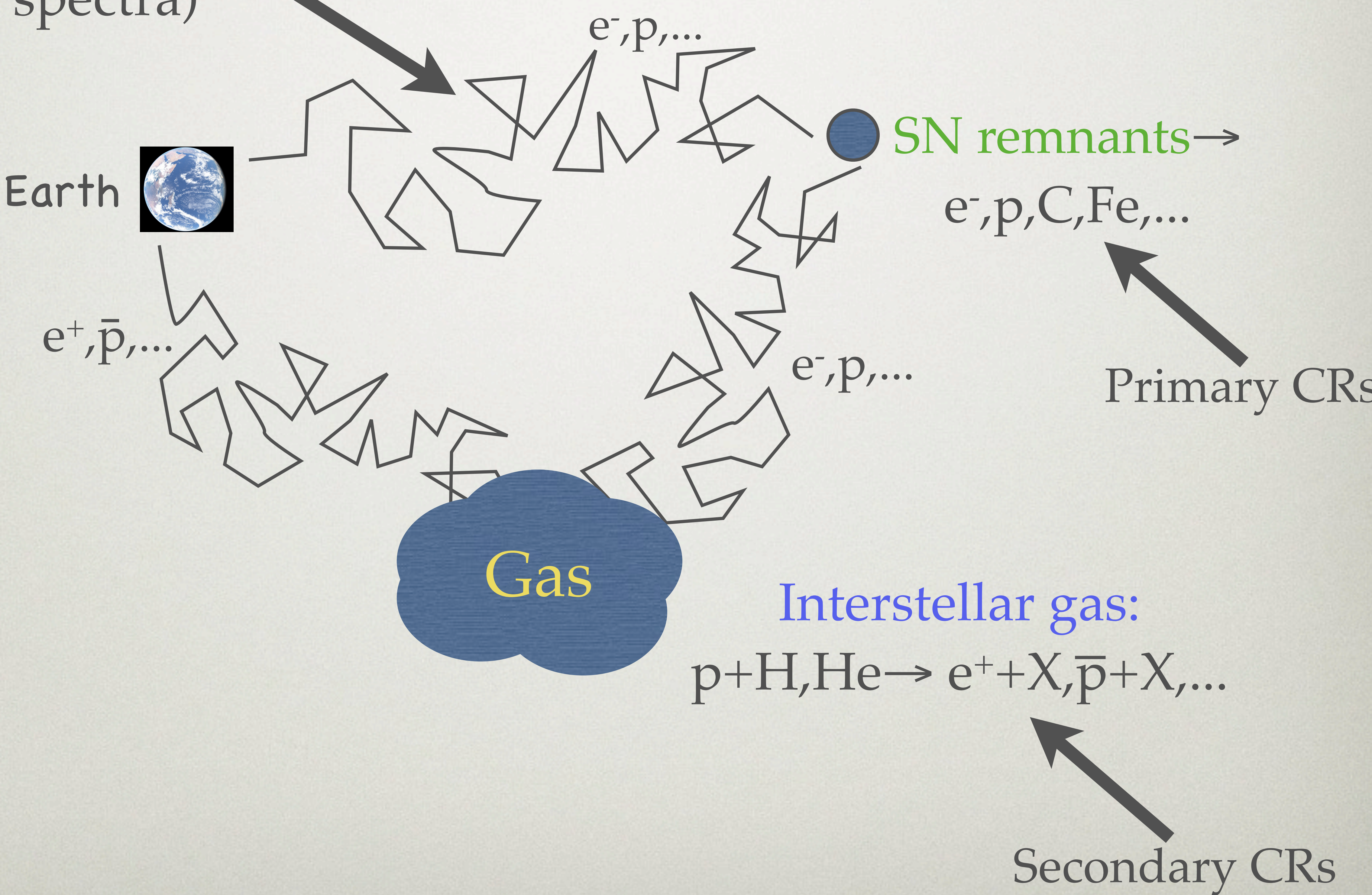
Cosmic Rays Propagation 101

Diffusion on turbulent galactic B field
(soften spectra)

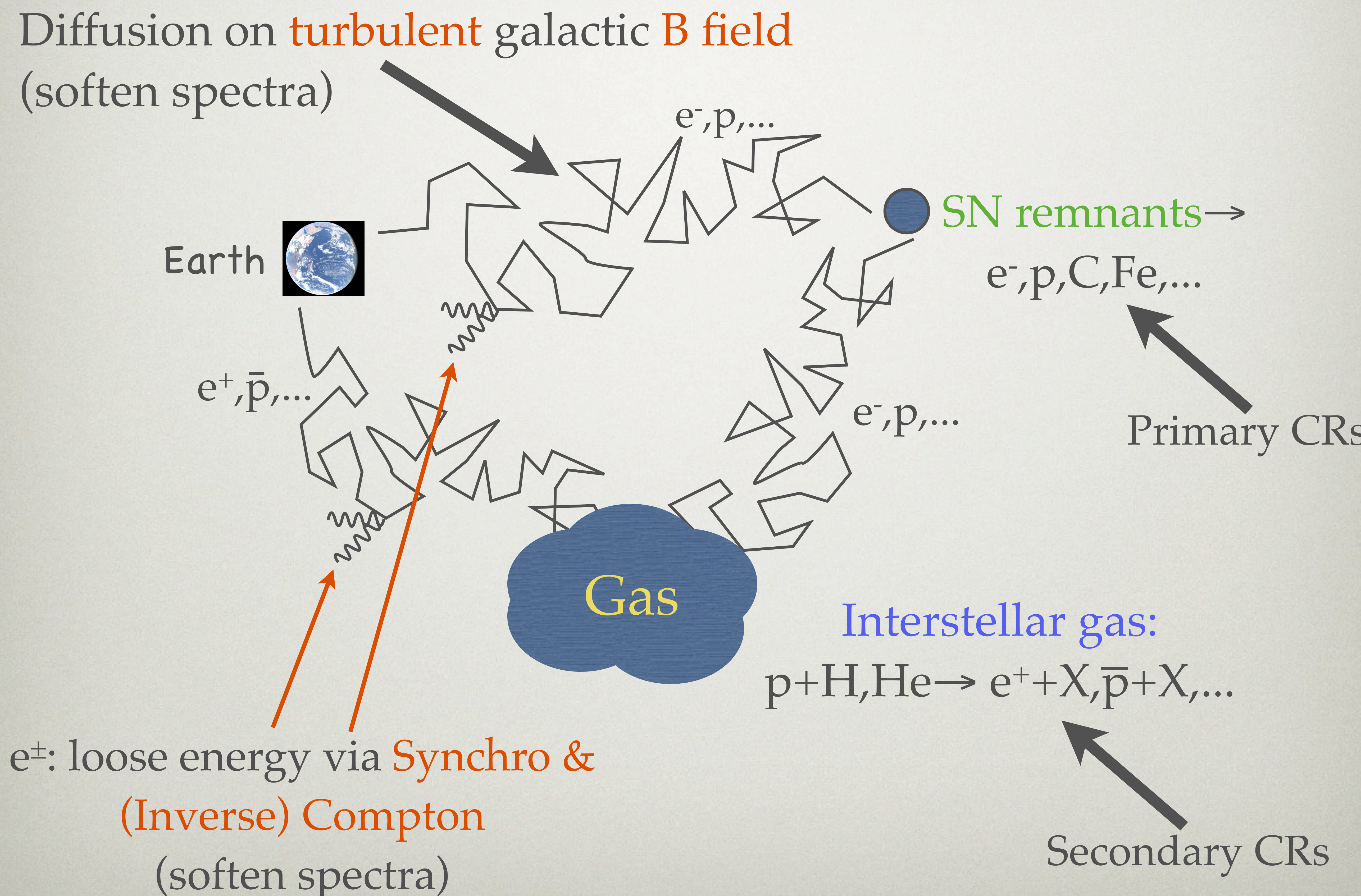


Cosmic Rays Propagation 101

Diffusion on turbulent galactic B field
(soften spectra)



Cosmic Rays Propagation 101



Cosmic Rays Propagation 101

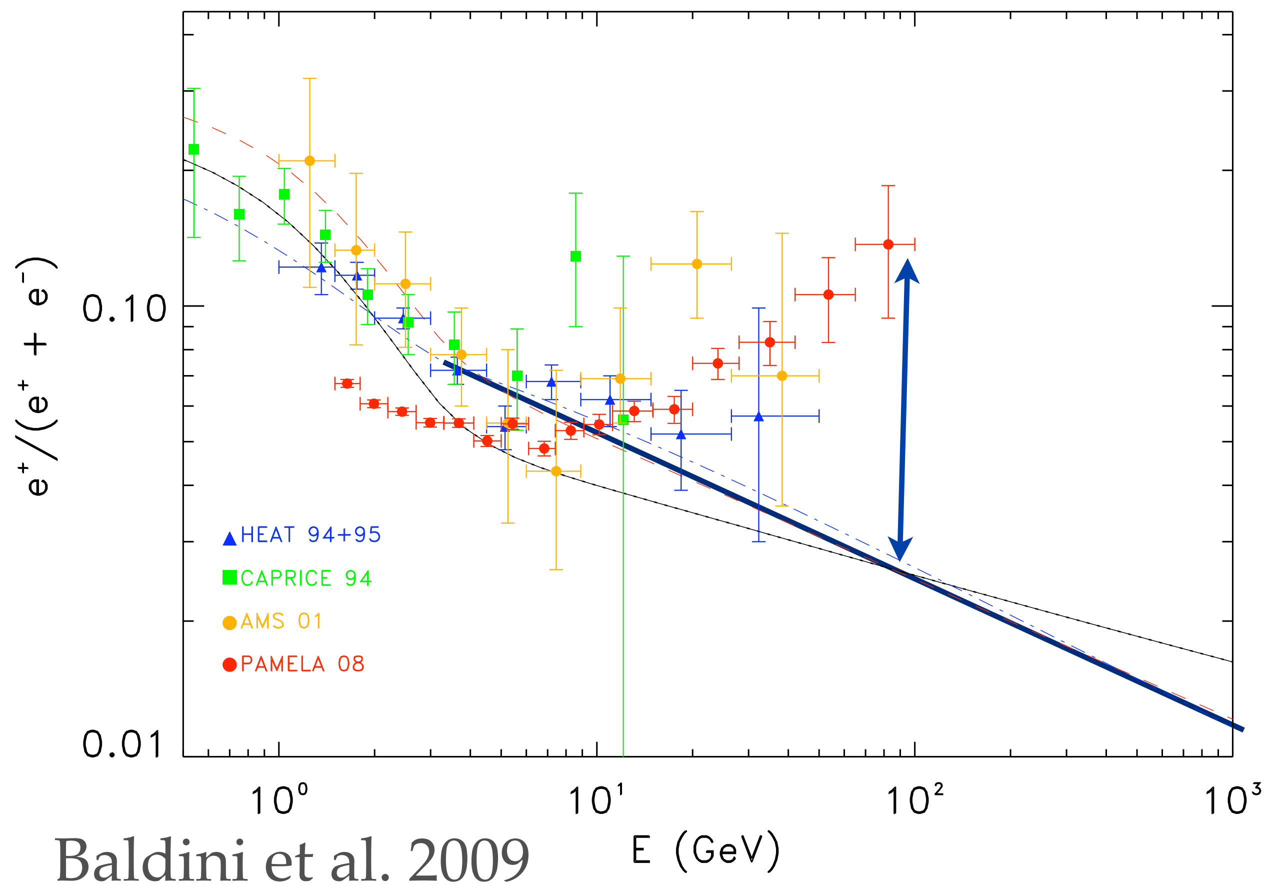
- Standard assumption: sources, gas, B-field, rad' field fairly homogeneous around us (~few kpc)

- Electron spectrum: measured
- Proton spectrum: measured

➡Compute e^+,$\bar{p}$ spectra

☞ Predictions for positron and antiproton fractions!

Cosmic Rays Propagation 101



Baldini et al. 2009

- FERMI measurement → the denominator in the positron fraction is under control
- PAMELA clearly observe a deviation from the standard picture

Why?

What can explain the excess?

- It's just Cosmic Ray Propagation:
  - Some of the assumptions about homogeneity (or energy dep') of sources and/or diffusion parameters are not good approx' at these energies (Katz, Waxman; Piran et al.)
- Positrons have also a primary component
  - SN Remnants (or their surroundings) may produce harder secondaries (Blasi; Blandford et al.)
  - New source(s) are needed...

What can explain the excess?

- New Astrophysical sources:
  - Positrons are created and accelerated in surroundings of pulsars (Pulsar Winds Nebulae)
  - Some nearby Pulsar may explain PAMELA and FERMI
  - HESS explanation: spectrum expected to be $E^a \exp(-E/E_c)$
  - Plausible but not clear how positrons can escape to the Interstellar Medium

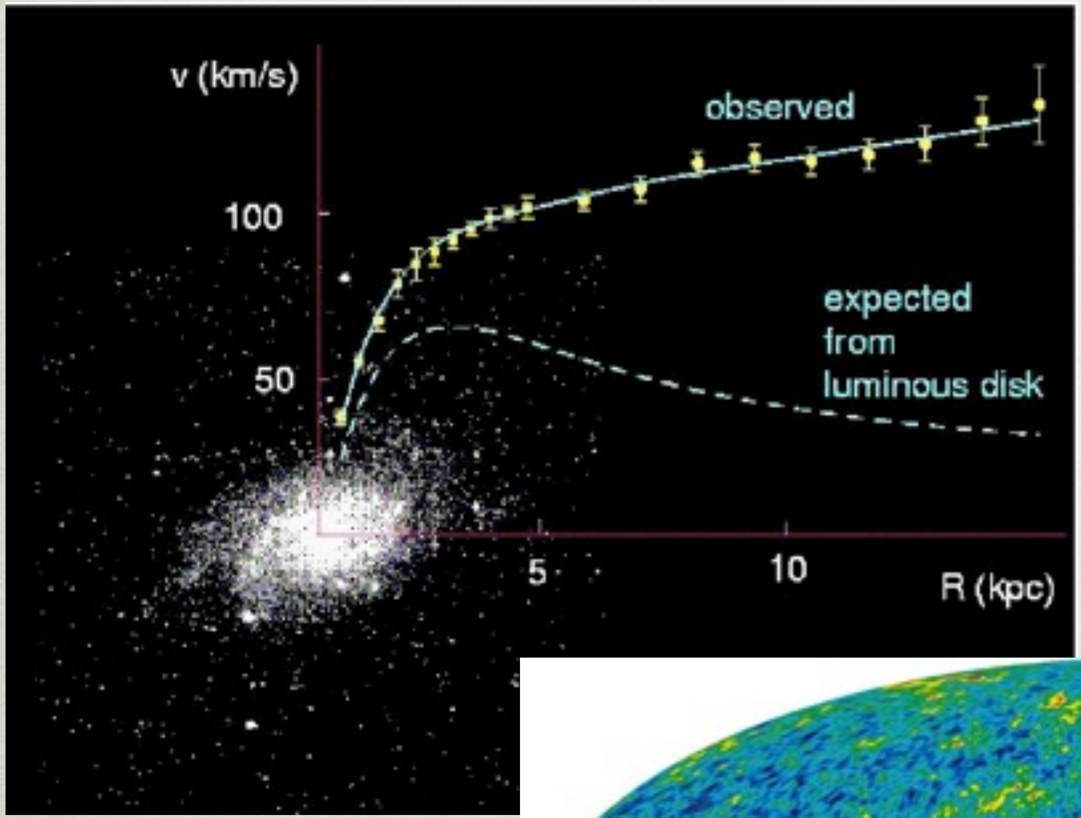
What can explain the excess?

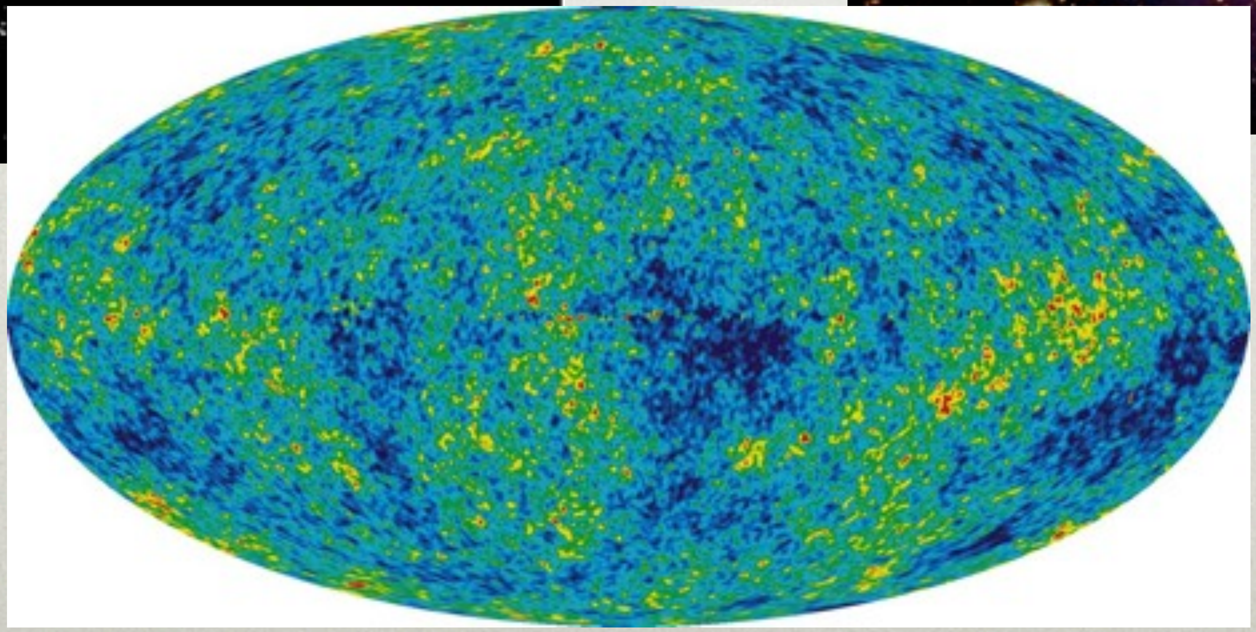
- New Astrophysical sources
- Indirect signal of Dark Matter:
  - Dark Matter in the Galactic Halo may annihilate or decay (on cosmological timescales)
  - Observed positrons (and electron excess) observed are DM products

☞ Explore this possibility in the rest of the talk....

Dark Matter

- Various evidences of DM from gravitational interactions





Dark Matter

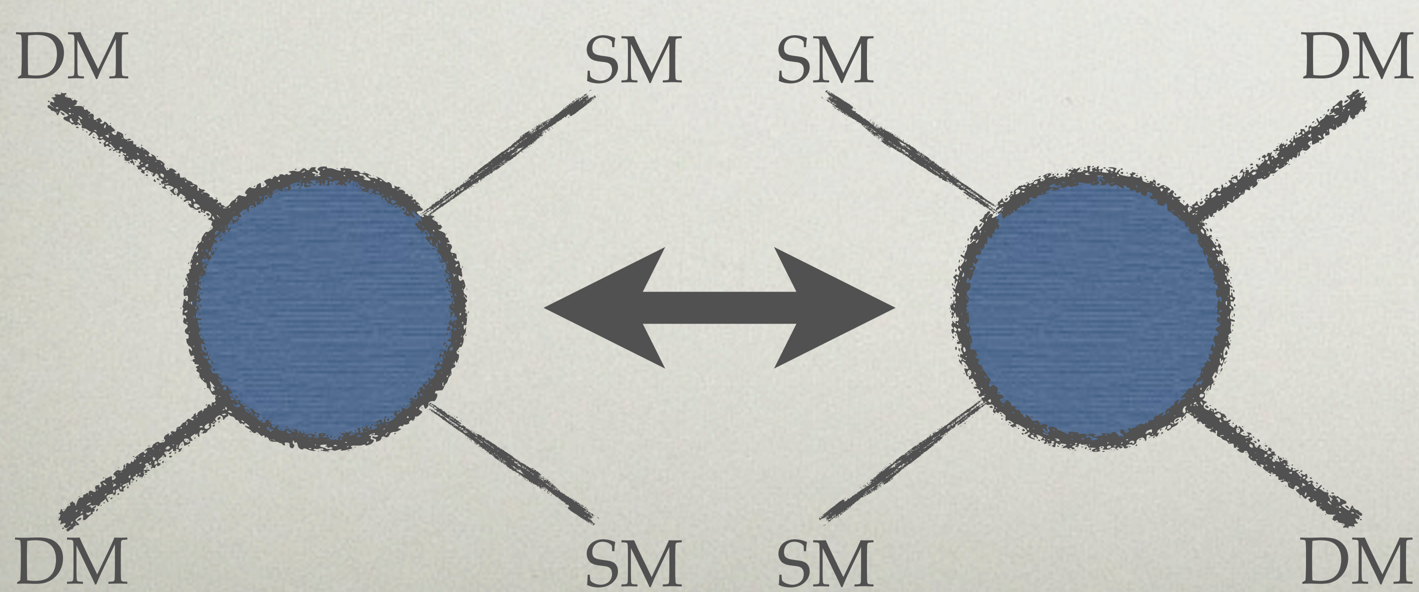
- Various evidences of DM from gravitational interactions
- Dark Matter is a neutral non-relativistic species (new particle!)

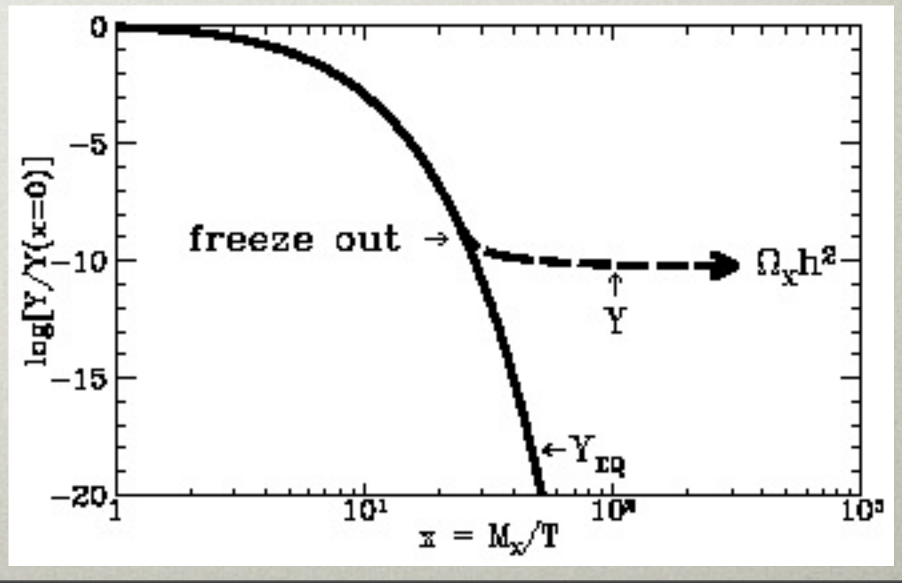
Dark Matter

- Various evidences of DM from gravitational interactions
- Dark Matter is a neutral non-relativistic species (new particle!)
- In our Galaxy $\langle v_{DM} \rangle \sim 10^{-3}c$

Dark Matter

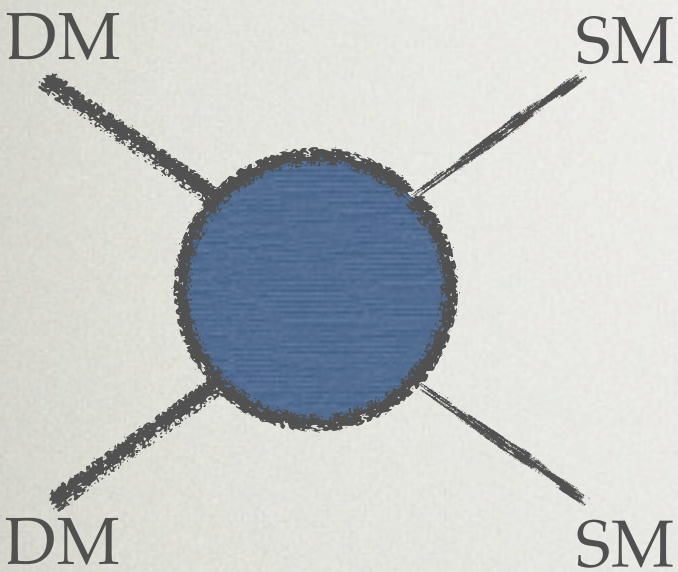
- Various evidences of DM from gravitational interactions
- Dark Matter is a neutral non-relativistic species (new particle!)
- In our Galaxy $\langle v_{DM} \rangle \sim 10^{-3} c$
- If DM thermal relic: $$\Omega_m h^2 \simeq 0.1 \left(\frac{3\ 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle_{freeze}} \right)$$

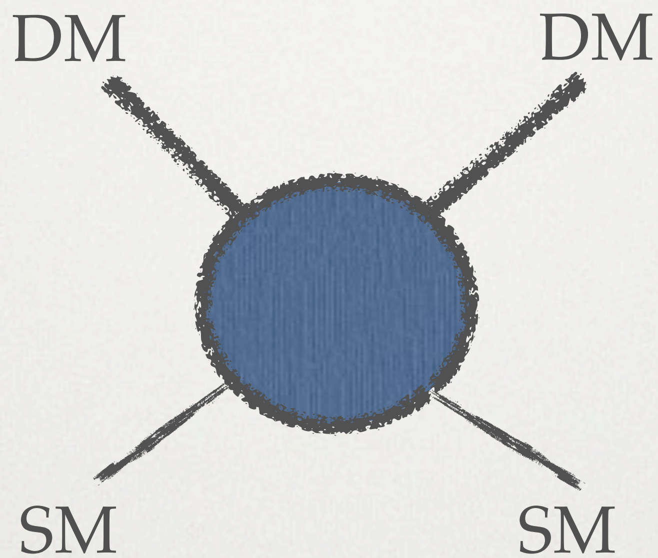


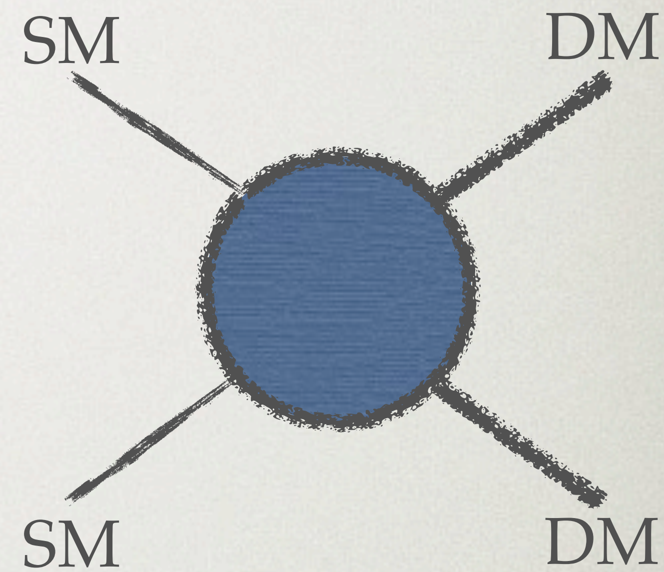


Same diagram, different channels...

Freeze-out:







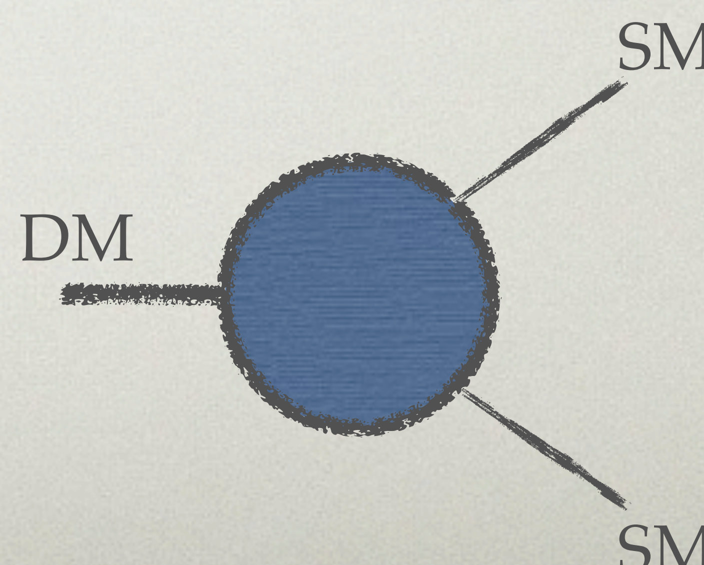
Indirect Detection
($\propto \varrho_{DM}^2$)

Direct Detection
($\propto \varrho_{DM}$)

Collider
Production

But also:

DM Decay
($\propto \varrho$, $\tau >> 13$Gyr)



Dark Matter Explanations of PAMELA

- Many models built in the past year(s)...

…various will be excluded in the following...

… a few scenarios still survive

(Model indep') Analysis

- DM annihilations/decays involving SM particles end up in electrons/positrons, (anti-)protons, photons, neutrinos.
- Electron, positrons, (anti-)protons are constrained by PAMELA & FERMI & HESS
- Photons are always present (charged particles in the final state)
- Neutrinos may or may not be present

➠ Fit PAMELA+FERMI+HESS and then look at gamma and neutrino observatories!

Relevant γ & ν data

- HESS measurements:
  - γ's from Galactic Center: $\vartheta < 0.1°$
  - γ's from Galactic "Ridge": $|b| < 0.3°$, $|l| < 0.8°$
- SuperKamiokande: ν's in cone up to 30° around Gal Center
- WMAP*
- Fermi: all sky gamma ray data

Relevant γ & ν data

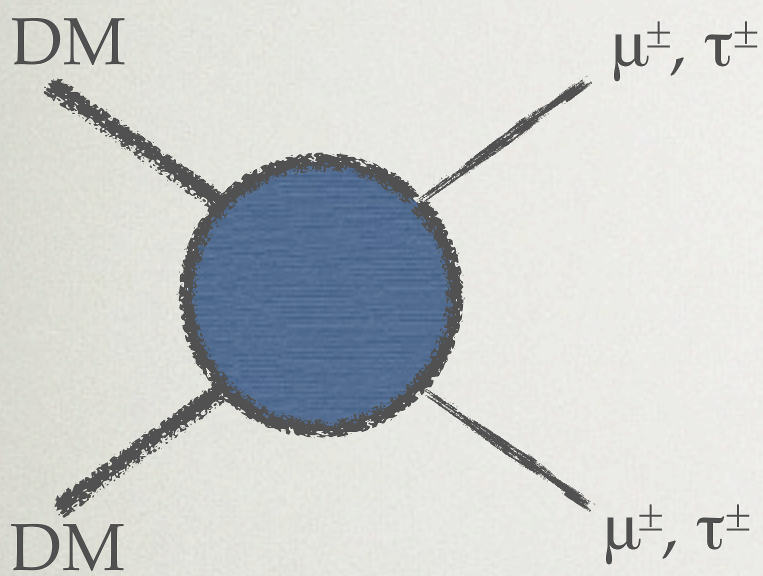
- HESS measurements:
  - γ's from Galactic Center: $\vartheta < 0.1°$
  - γ's from Galactic "Ridge": $|b| < 0.3°$, $|l| < 0.8°$
- SuperKamiokande: ν's in cone up to 30° around Gal Center
- WMAP*
- Fermi: all sky gamma ray data

→ Strongest constraints!

Fit Ingredients

- DM annihilates / decays almost at rest. Relevant info:
  - DM Mass (sets energy scale)
  - Annihilation / Decay Rate
  - Final states (determines e±, γ, ν, p injection spectra)
  - DM density profile (uncert.)

Fits Results: Final States



Only μ, τ Leptons

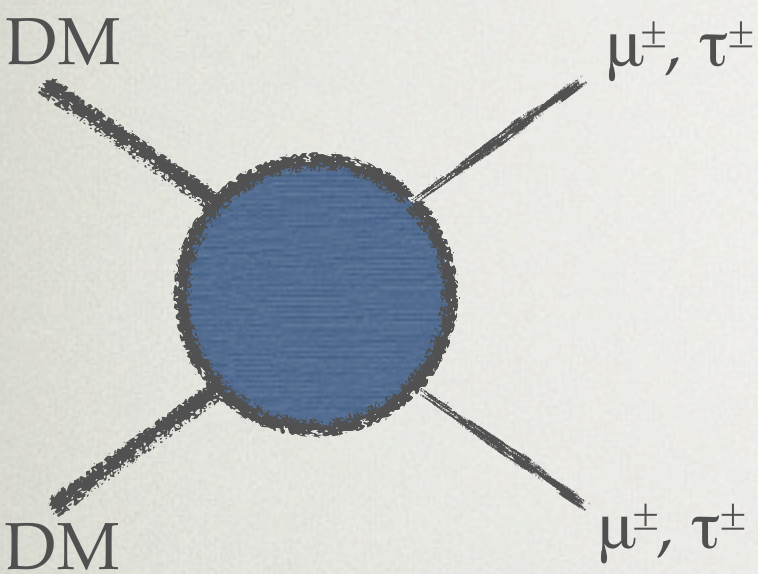
($e^\pm$ too hard spectrum,

$\mu^\pm$ not a great fit)

No W, Z, h, quarks

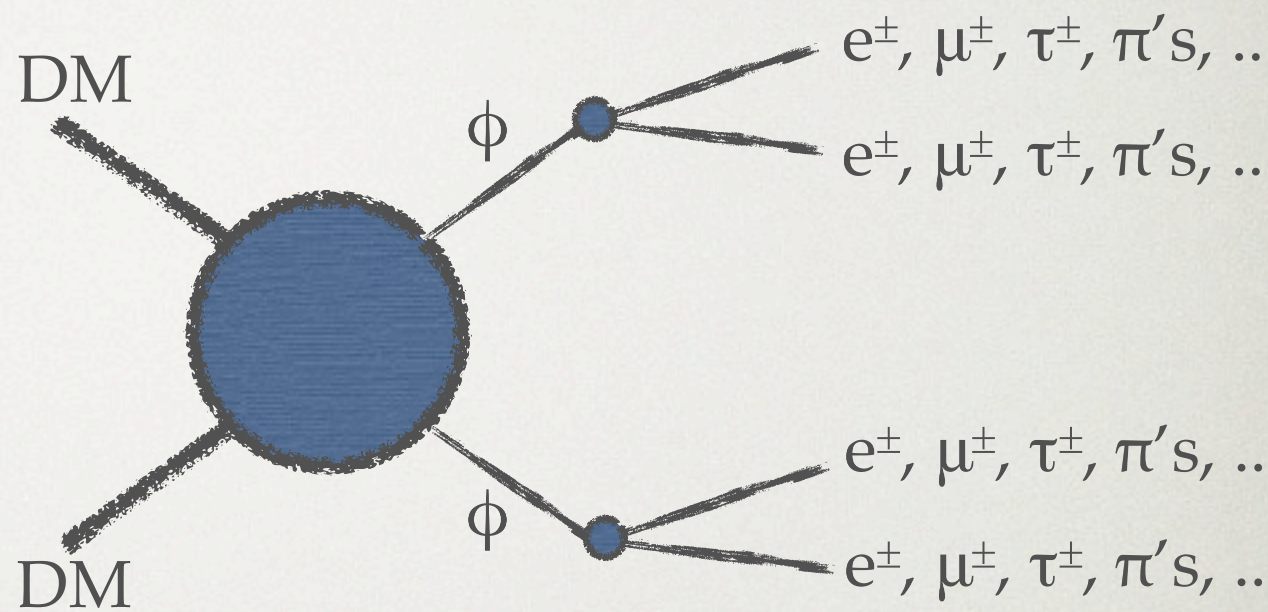
→ too many antiprotons

Fits Results: Final States



Only μ, τ Leptons

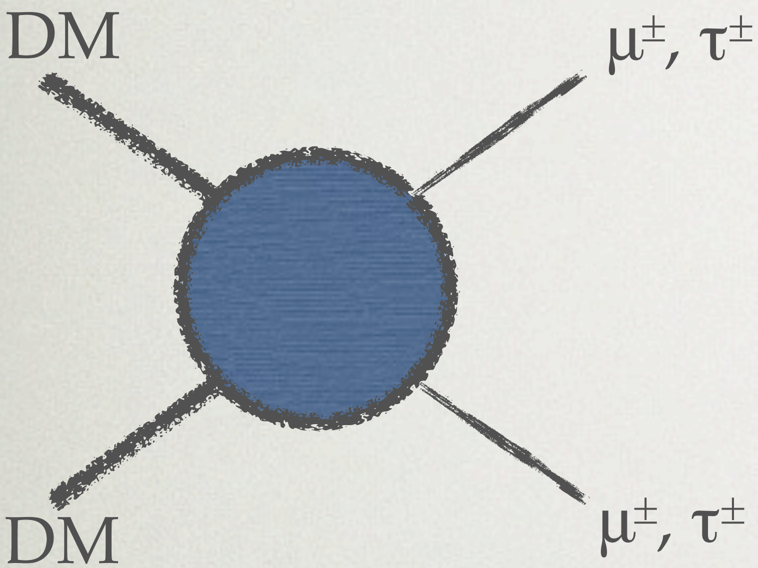
($e^{\pm}$ too hard spectrum, $\mu^{\pm}$ not a great fit)



All leptons and light mesons

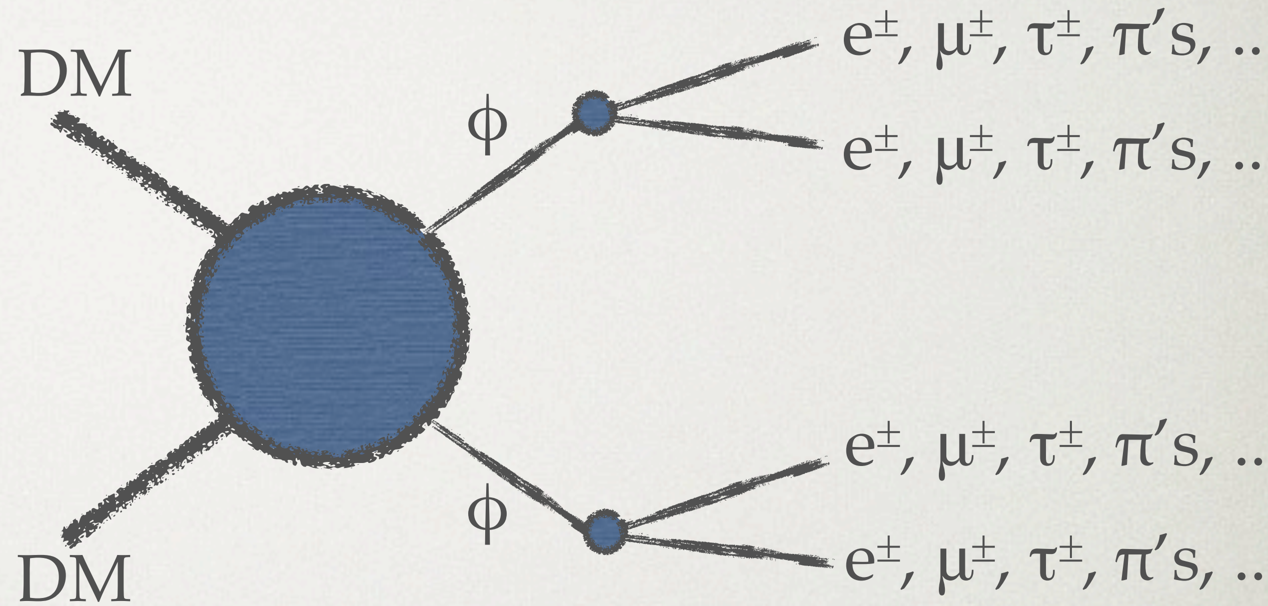
Requires a new light particle!!

Fits Results: Final States



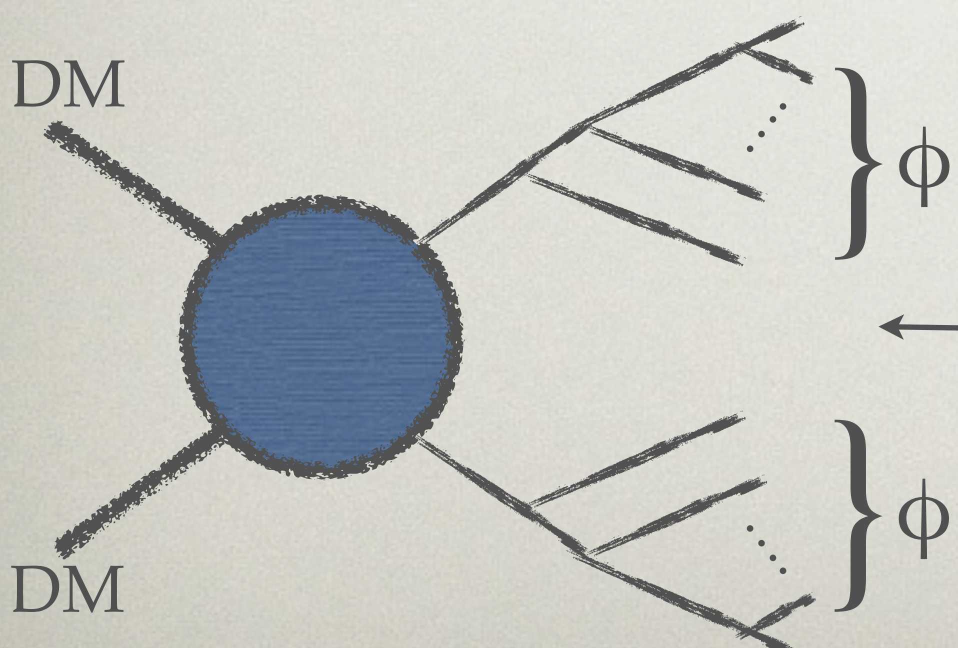
Only μ, τ Leptons

($e^\pm$ too hard spectrum, $\mu^\pm$ not a great fit)



All leptons and light mesons

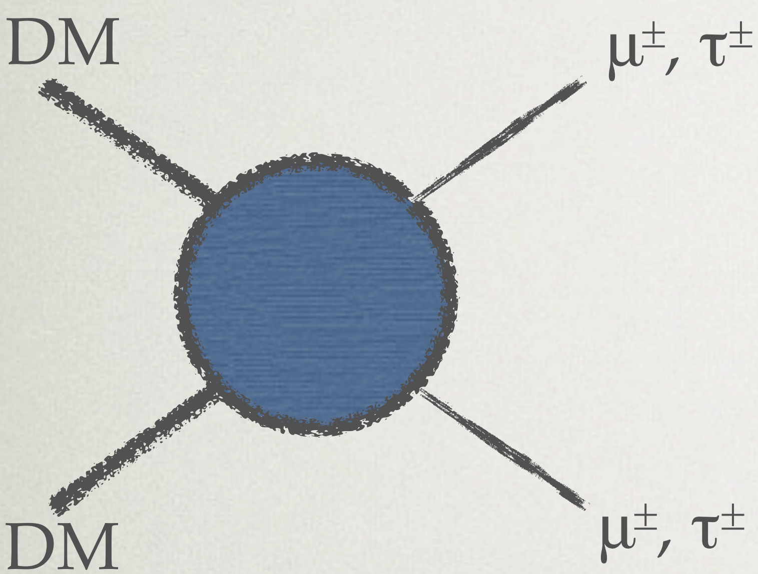
Requires a new light particle!!



"Hidden" shower, softer spectra, better fits

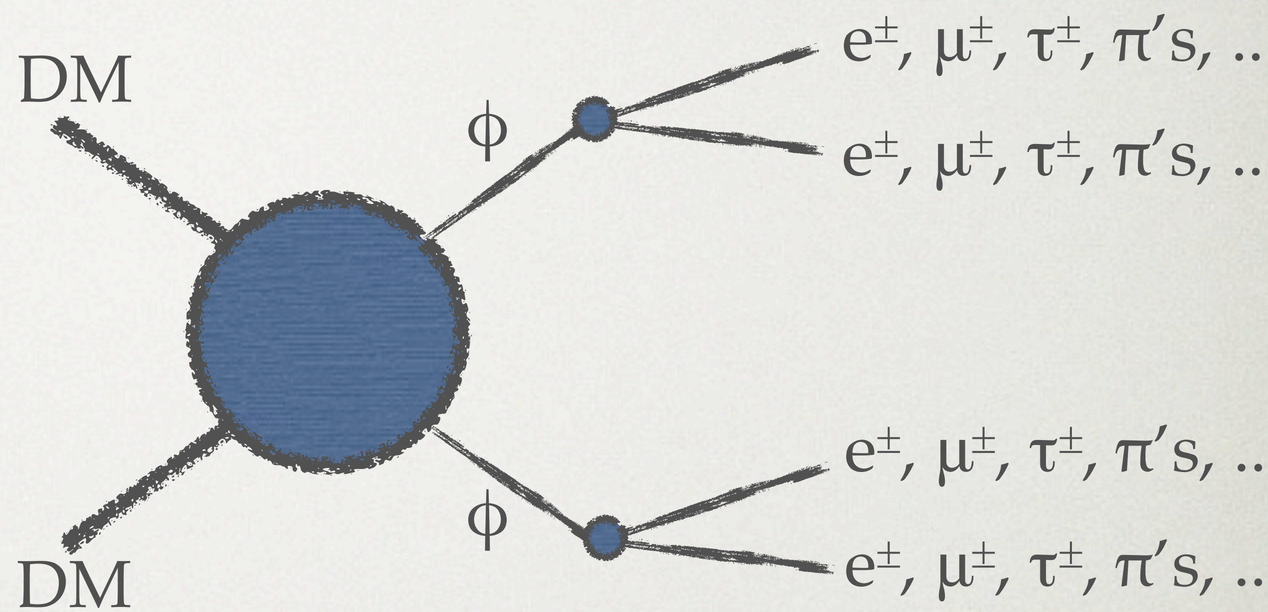
(e.g. ϕ spin 1 in non-Abelian gauge group)

Fits Results: Final States



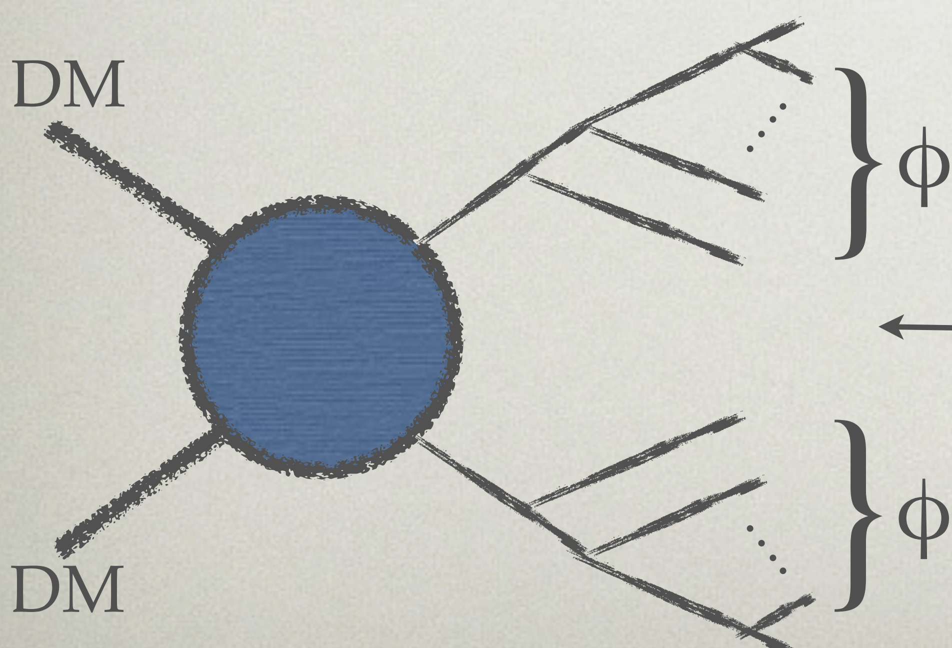
Only μ, τ Leptons

($e^\pm$ too hard spectrum, $\mu^\pm$ not a great fit)



All leptons and light mesons

Requires a new light particle!!



"Hidden" shower, softer spectra, better fits

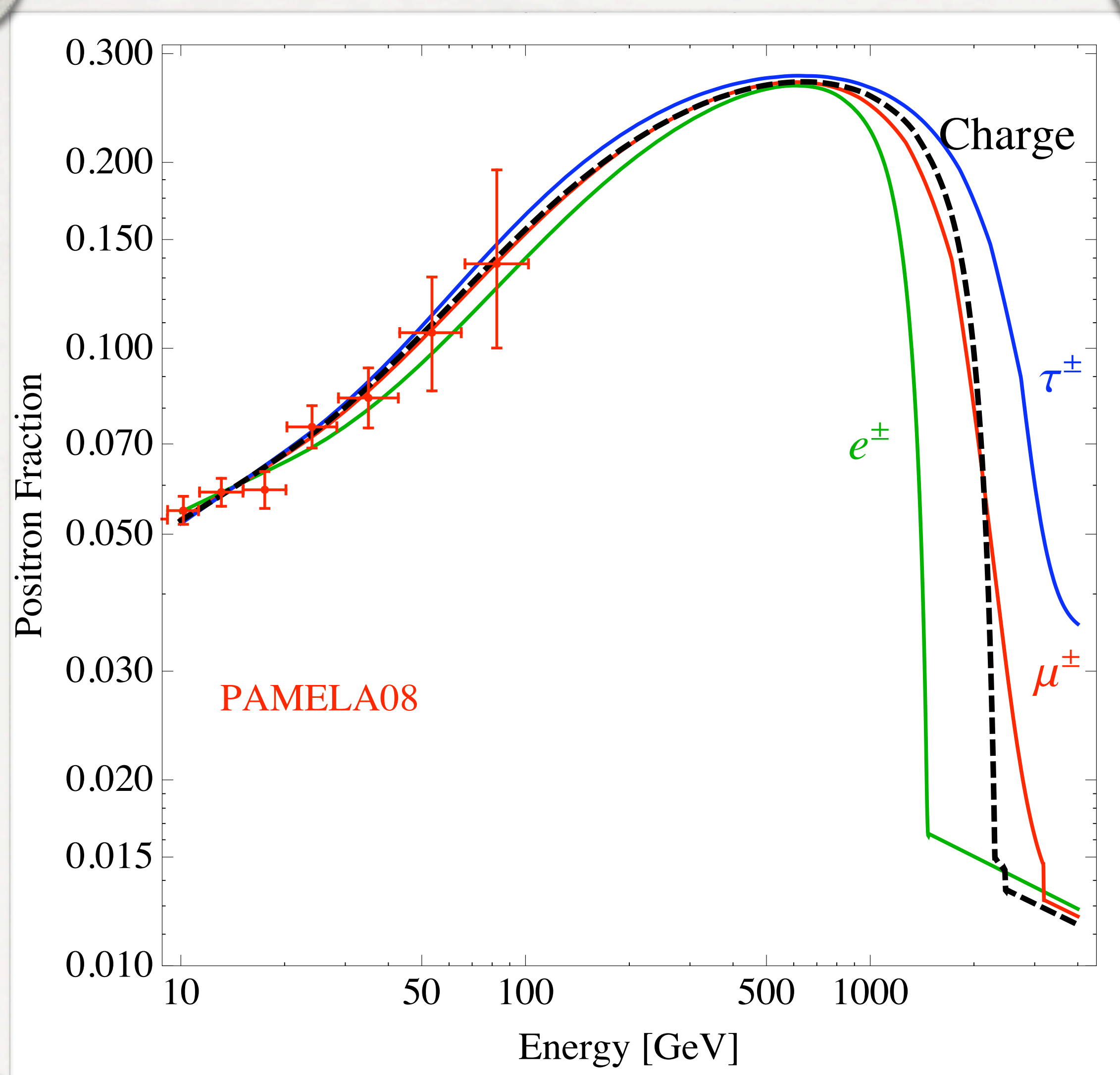
(e.g. ϕ spin 1 in non-Abelian gauge group)

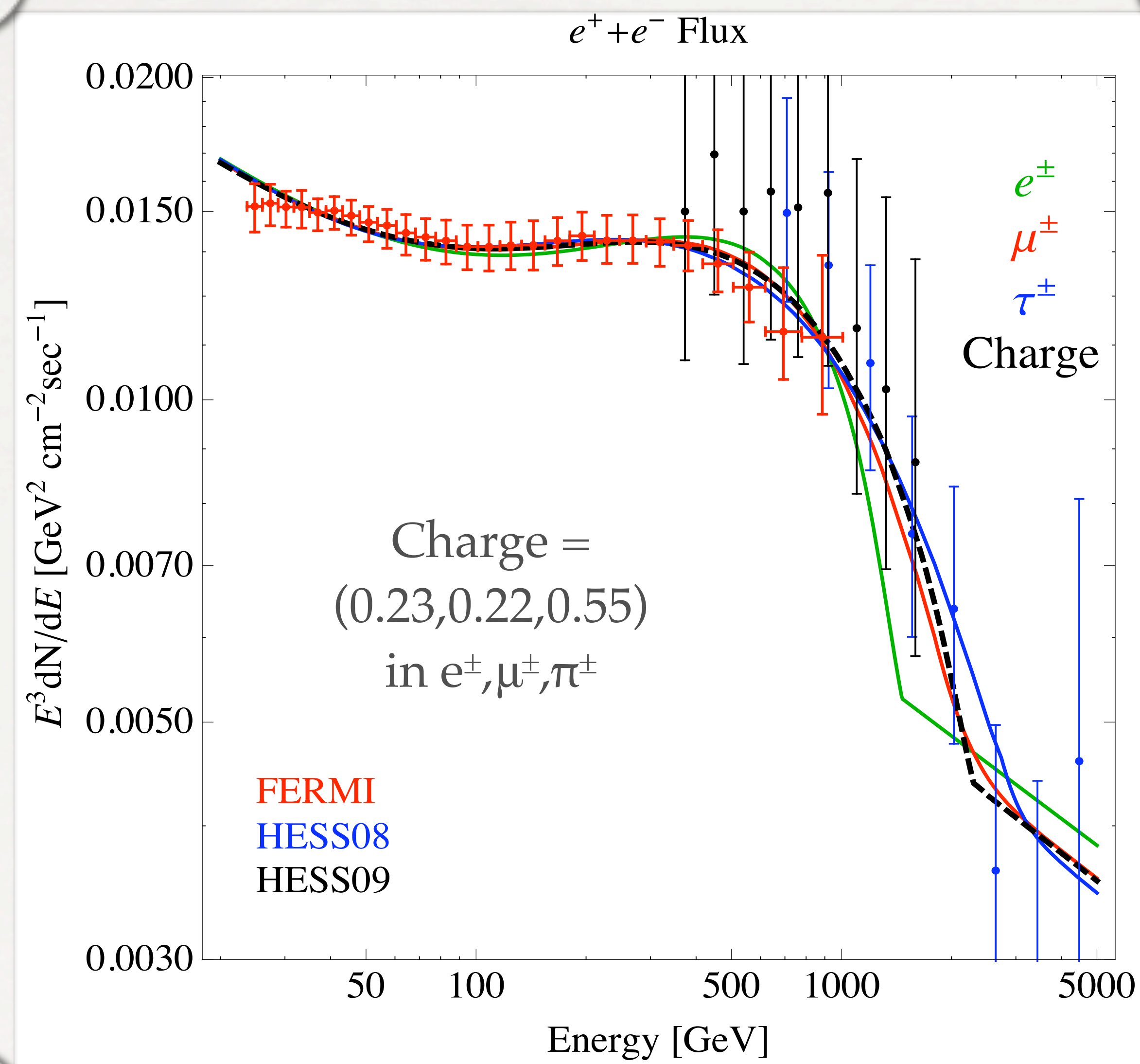
And the same for decaying DM...

Best fits

Injection spectra: the shallower, the better

4-body preferred over 2-body





4body ann', Einasto

Fits Results: Mass and Rates

- Large mass (HESS cutoff):
  - Annihilating: M_{DM}> 1-1.5 TeV
  - Decaying: M_{DM}> 2-3 TeV
- Large rate:
  - Decaying: $1/\Gamma \sim 10^{26}$ s

    e.g. with GUT-scale suppressed operator (proton decay-like)

    (Arvanitaki et al.)
  - Annihilating: $\langle\sigma v\rangle \sim 10^{-23}\ \mathrm{cm^3 s^{-1}}$

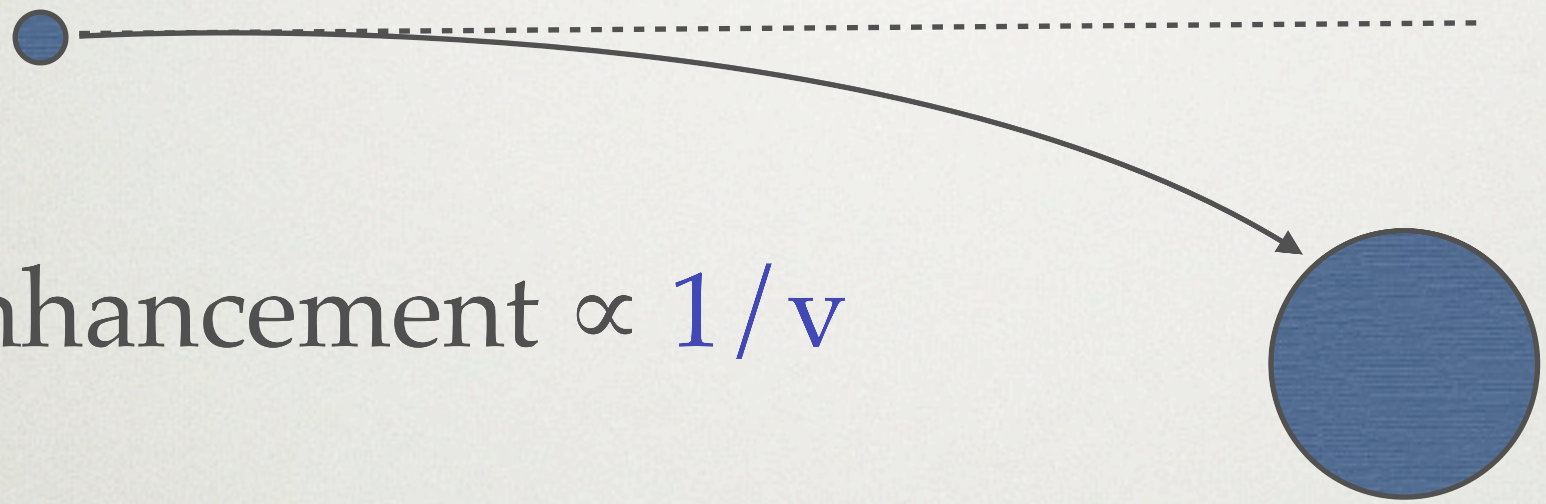
    O(1000) larger than thermal freeze-out xsec!!

    Particle Physics explanation: Sommerfeld enhancement

    ("comes for free" with 4 body final states)

Sommerfeld Enhancement

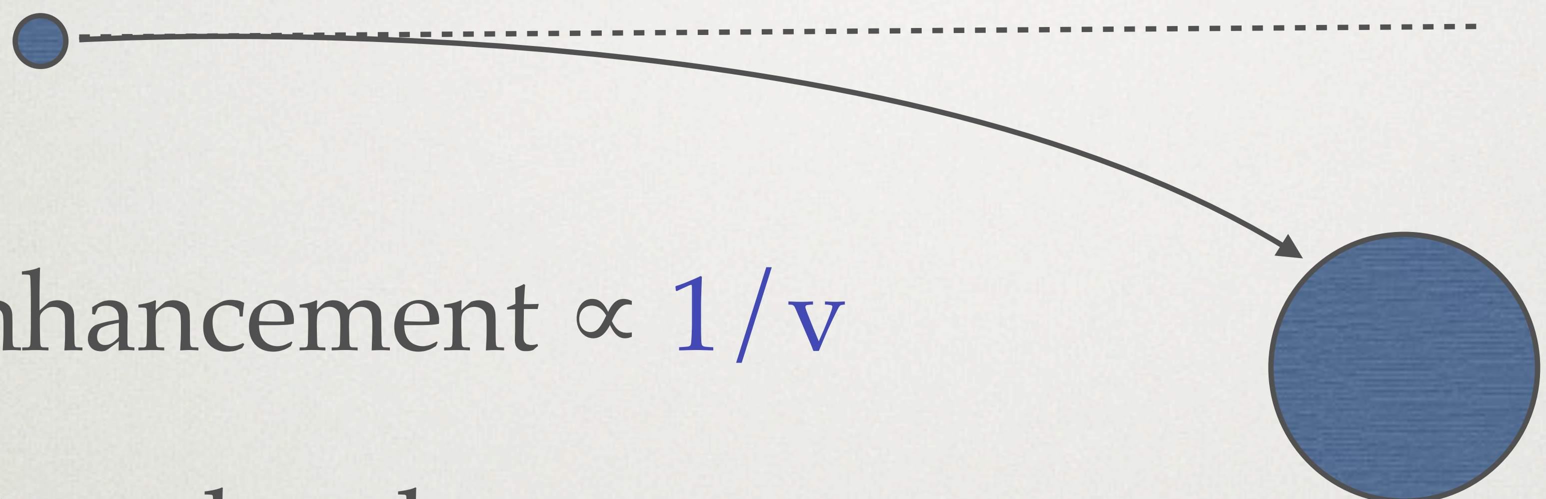
- If a long range force present, xsec can be enhanced (already at classical level):



Enhancement $\propto 1/v$

Sommerfeld Enhancement

- If a long range force present, xsec can be enhanced (already at classical level):



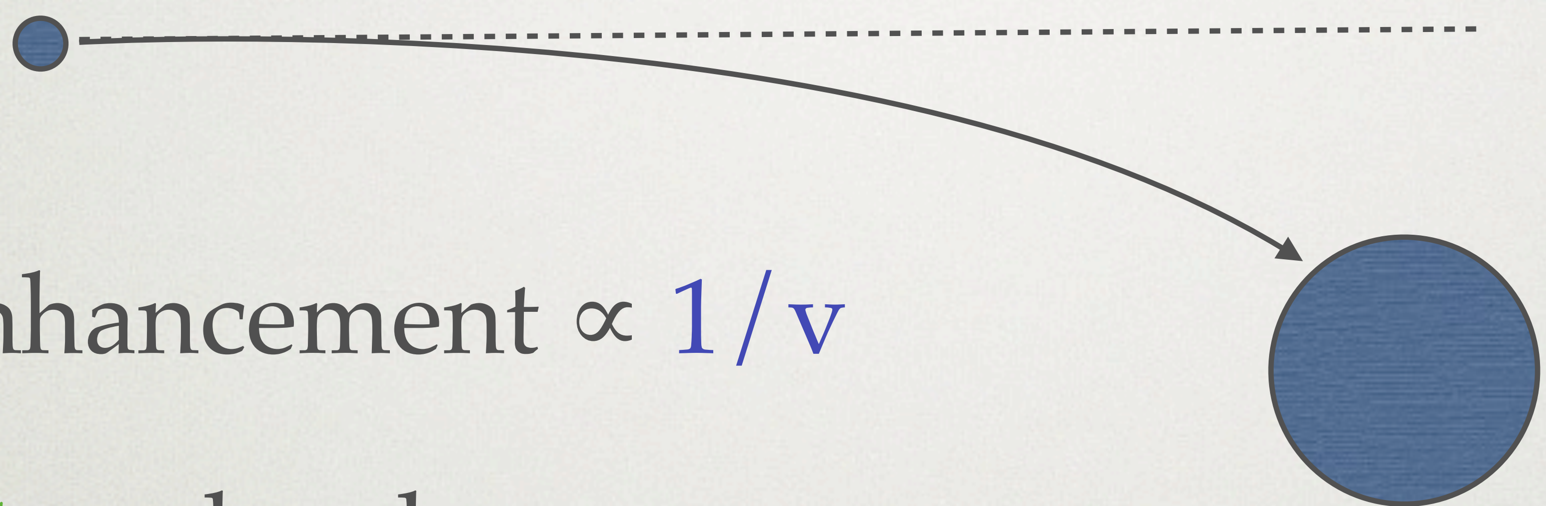
Enhancement $\propto 1/v$

Quantum level:

- Enhancement saturates when deBroglie w.l. > force range
- Resonances may be present for discrete values of the params
- Effect present also if interaction is among two different mass states as long as ΔM is small enough

Sommerfeld Enhancement

- If a long range force present, xsec can be enhanced (already at classical level):



Enhancement $\propto 1/v$

Quantum level:

•Enhancement saturates when deBroglie w.l. > force range

•Resonances may be present for discrete values of the params

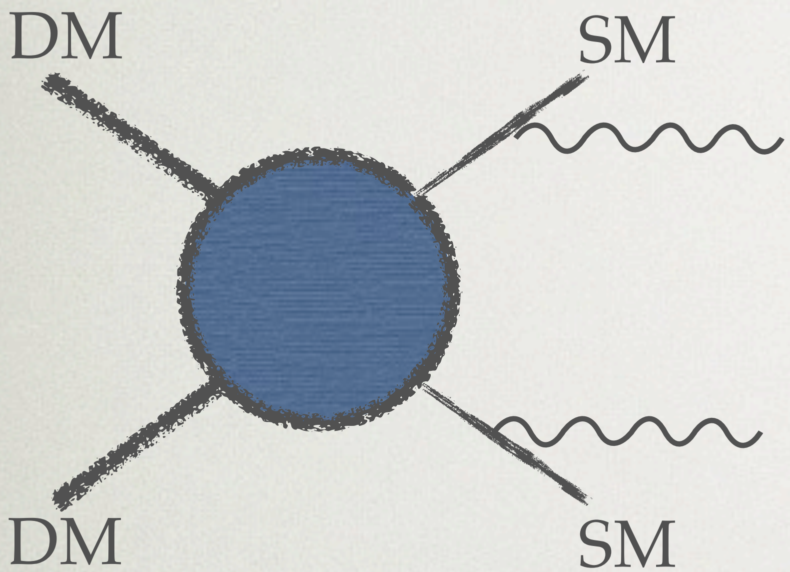
•Effect present also if interaction is among two different mass states as long as ΔM is small enough

"Long distance" for TeV DM $\rightarrow$ 1 fm

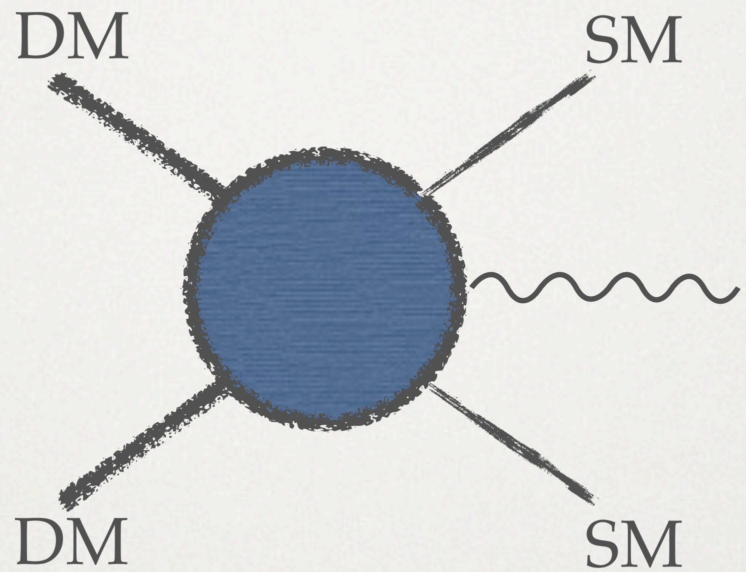
0.1÷1 GeV force carrier!!

Looking at the γ constraints...

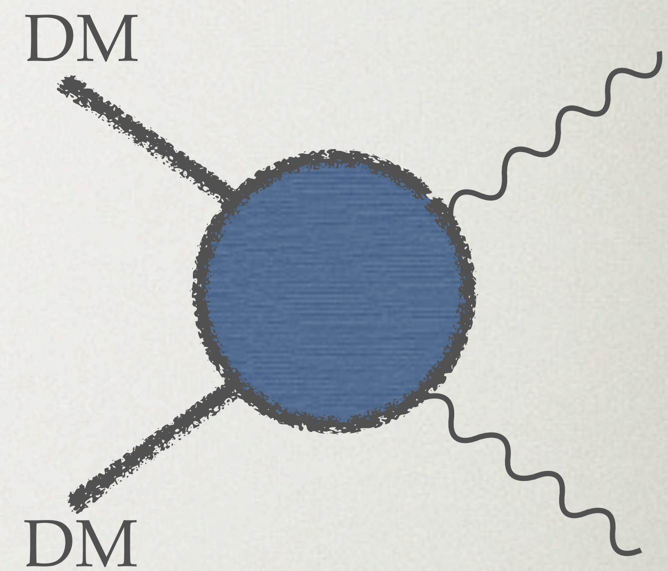
Many photons to consider



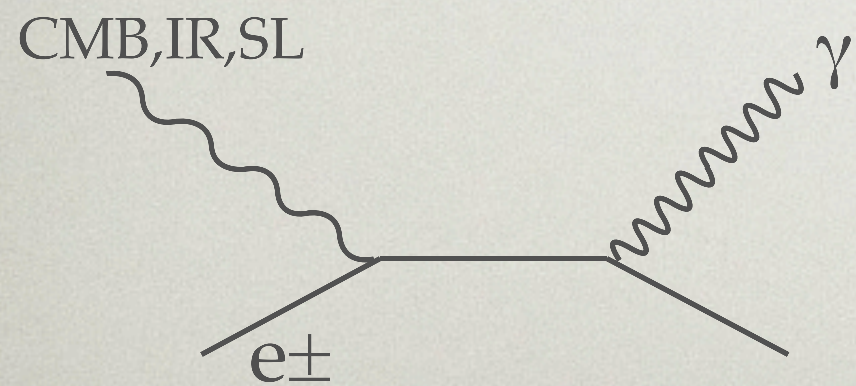
Final State Rad′
(soft+collinear)



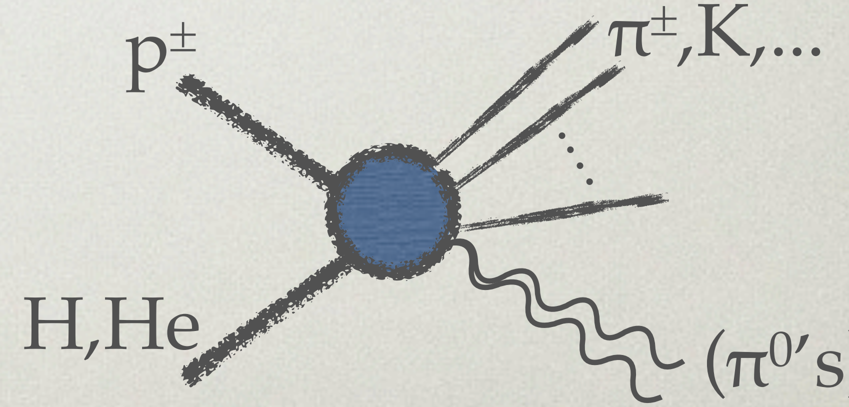
Hard emission



Higher order processes

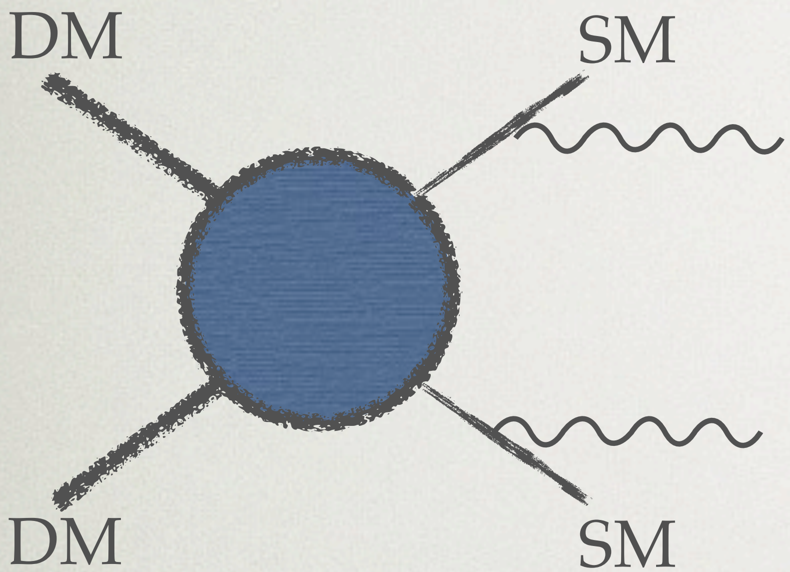


Inverse Compton



γ′s from proton int′ with ISM

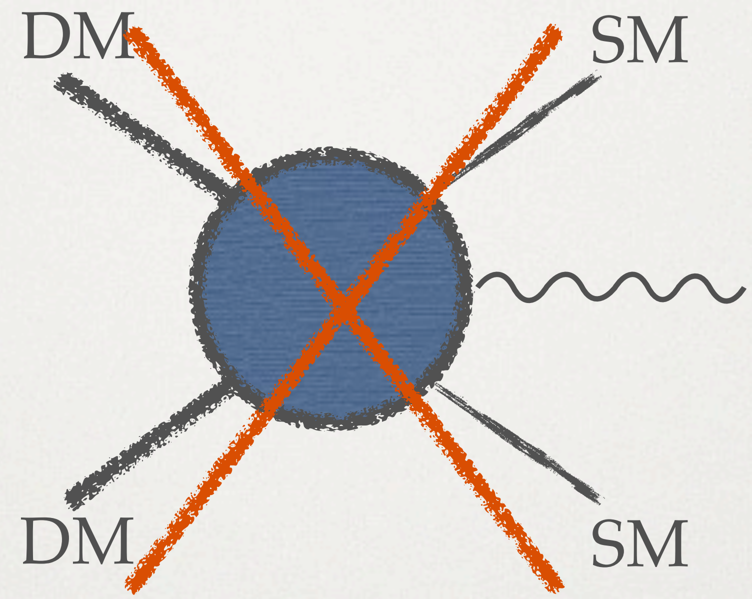
Many photons to consider



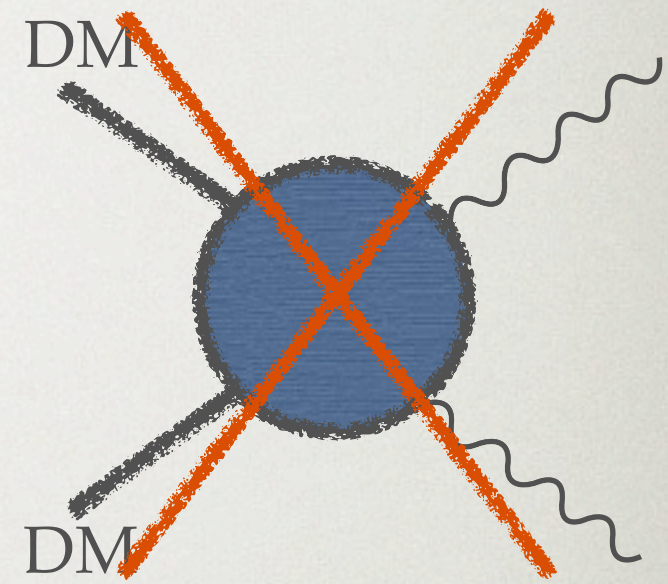
Final State Rad′

(soft+collinear)

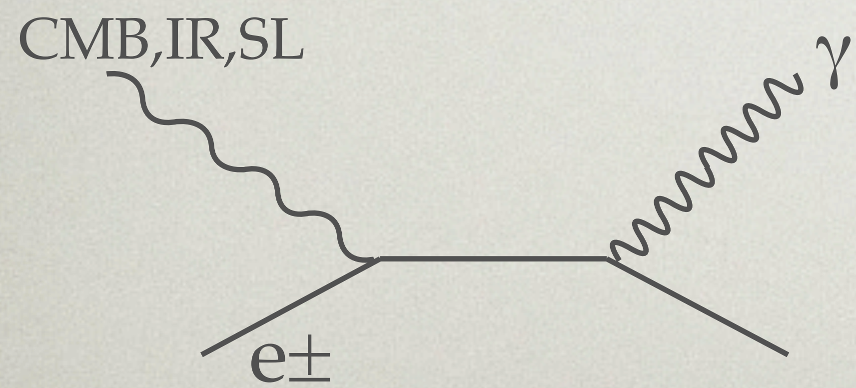
+ γ′s from hadro decays



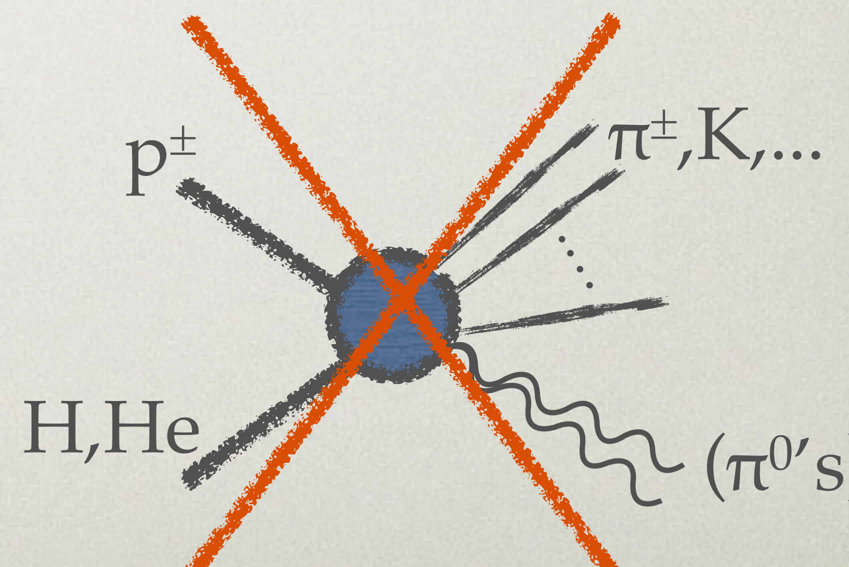
Hard emission



Higher order processes



Inverse Compton

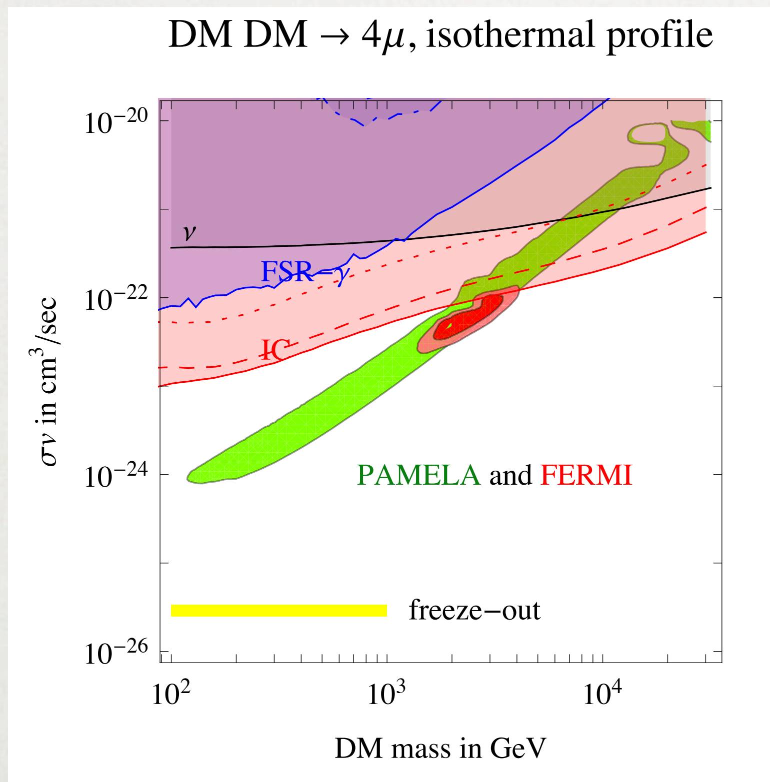


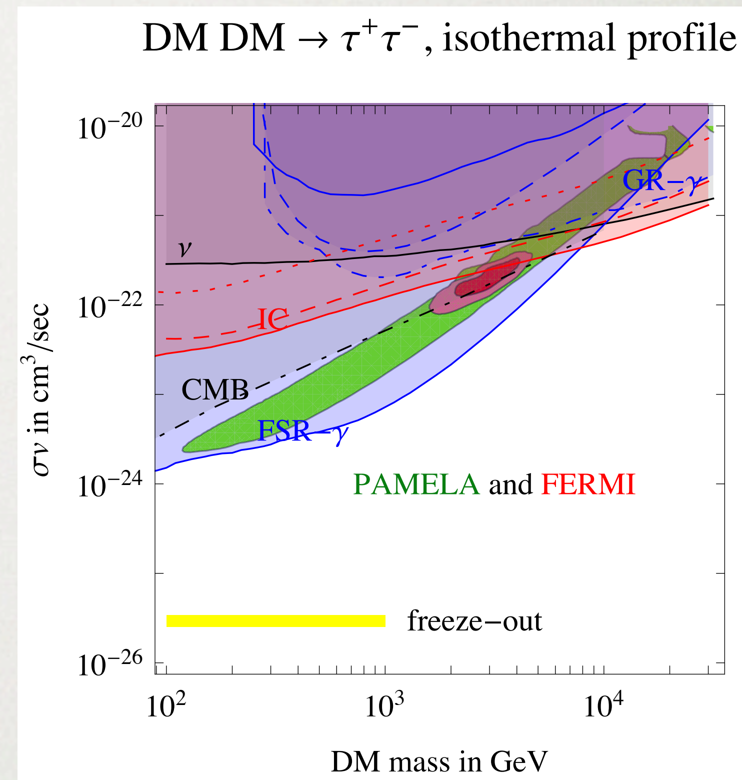
γ′s from proton int′ with ISM

Fits vs γ bounds

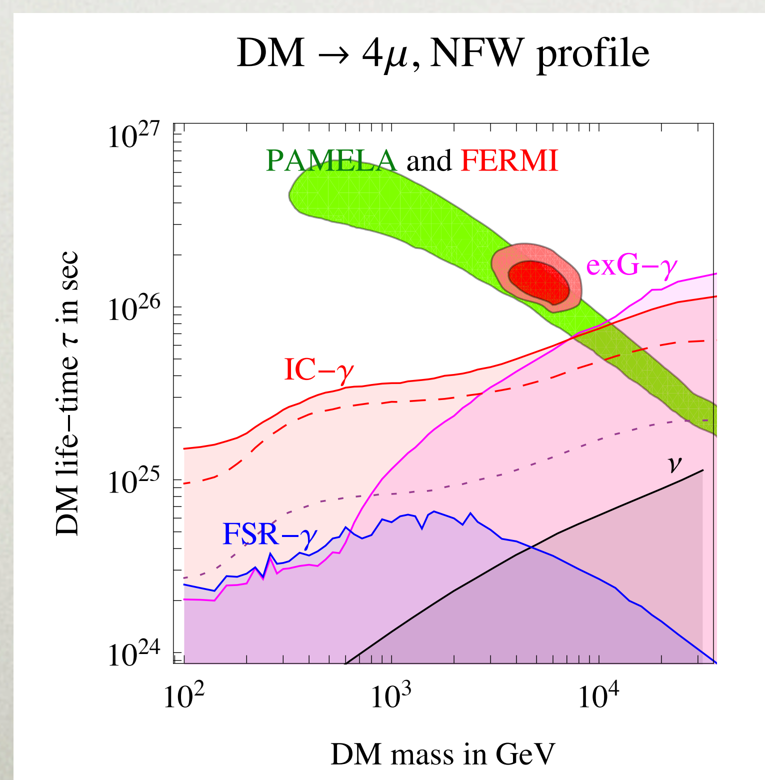
Final states: 4μ 2τ

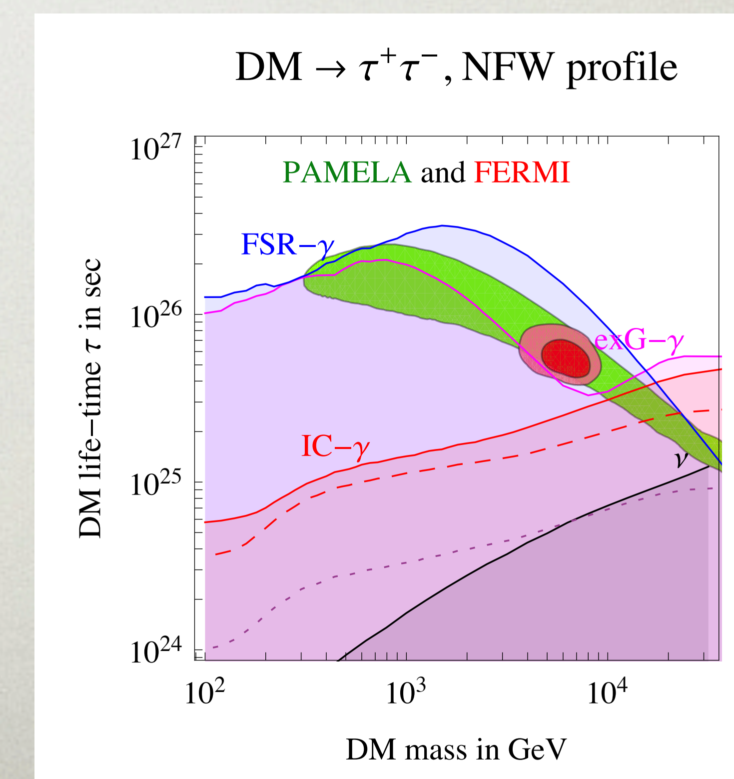
DM Annihilation





DM Decay





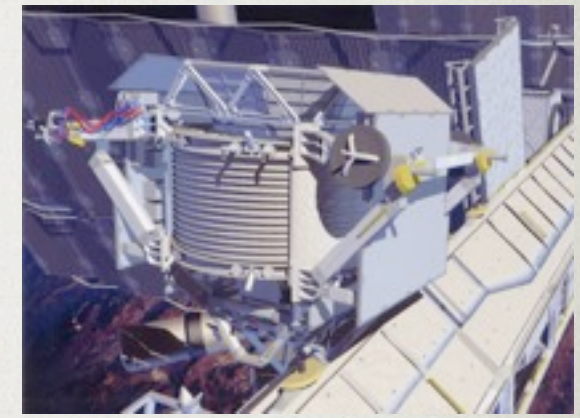
Fermi γ constraints

- Final states with too much hard radiation (π^0's in τ's) are now excluded both in annihilating and decay models
  - No way to hide signals with the Annihilating vs. Decay (ϱ^2 vs ϱ "trick" that worked for the Galactic Center)
- Other leptonic 4-body final states are close to the bounds (slight tension in annihilating models for cuspy profiles ~ factor of 2. Uncert' larger)
- Overall bounds are quite robust (see tomorrow's talk)

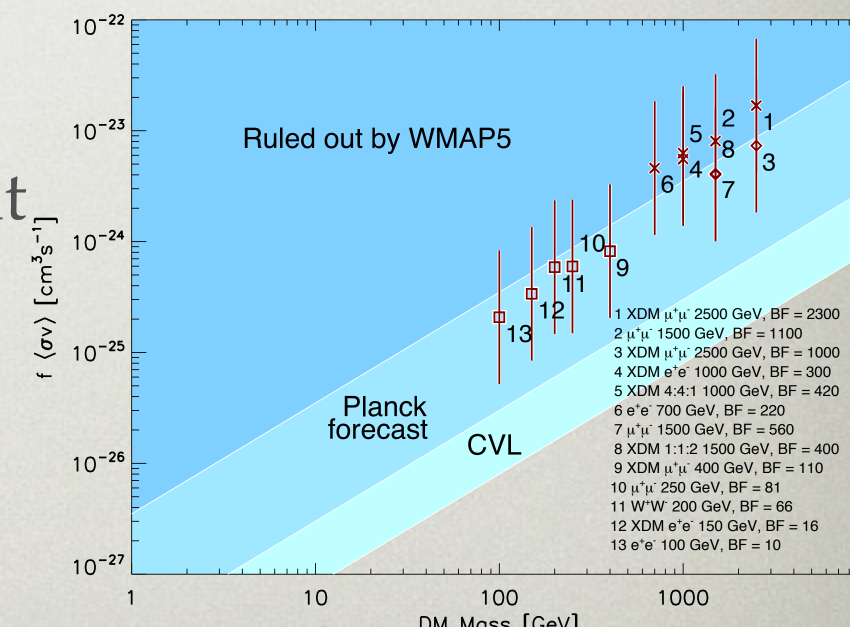
☞ DM should give O(1) fraction of γ emission at high energy

☞ Preference to "hidden sector" models coupling to e,μ,π

Making Progress



- AMS02: can tell whether positron fraction will continue to increase or not (necessary if DM is heavy); will drastically reduce CR propagation uncert'; will test some of the astro explanations
- FERMI: Better bounds from less contaminated γ events and/or higher energy. Possible detection of DM subhalos $\rightarrow$ Crucial to test the DM hypothesis, both for annihilating and for decay
- Planck: very robust bounds from energy injection at recombination time can close the window for annihilating DM (Finkbeiner et al. 2009, Bertone et al. 2009)
- Xenon/Lux: DM direct detection may have the chance to clarify the whole picture



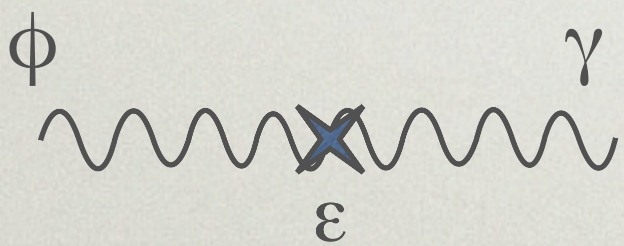
Hidden Sectors?

- DM models presented so far → new light particles
- Haven't seen them yet → coupling with the Standard Model should be small

Easy to get!

"Vector portal"

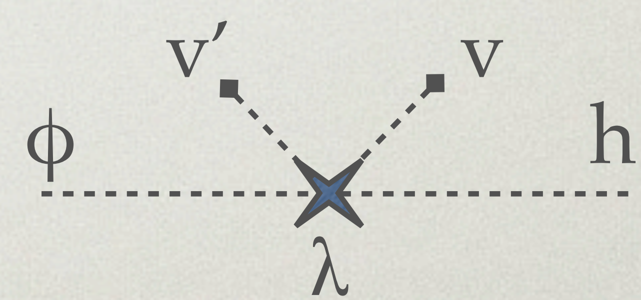
$$\epsilon\, \Phi_{\mu\nu}\, F^{\mu\nu}$$



Coupling ∝ $\varepsilon\, e\, Q$

"Higgs portal"

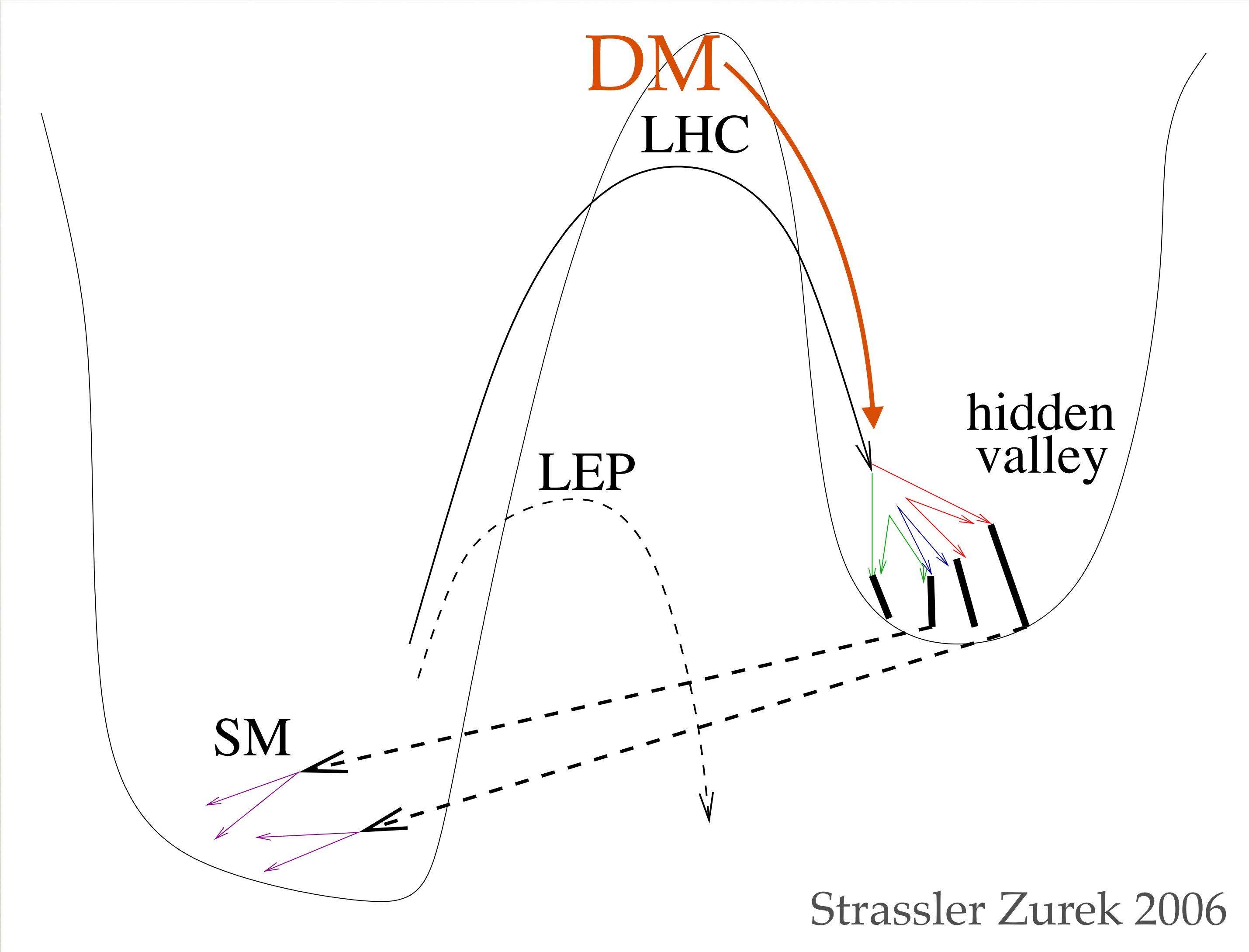
$$\lambda|\phi|^2|H|^2$$



Coupling ∝ $10^{-2}\, \lambda\, y_f$

Hidden Valleys & Co.

Pheno interests in "hidden sectors" have been around for a while...

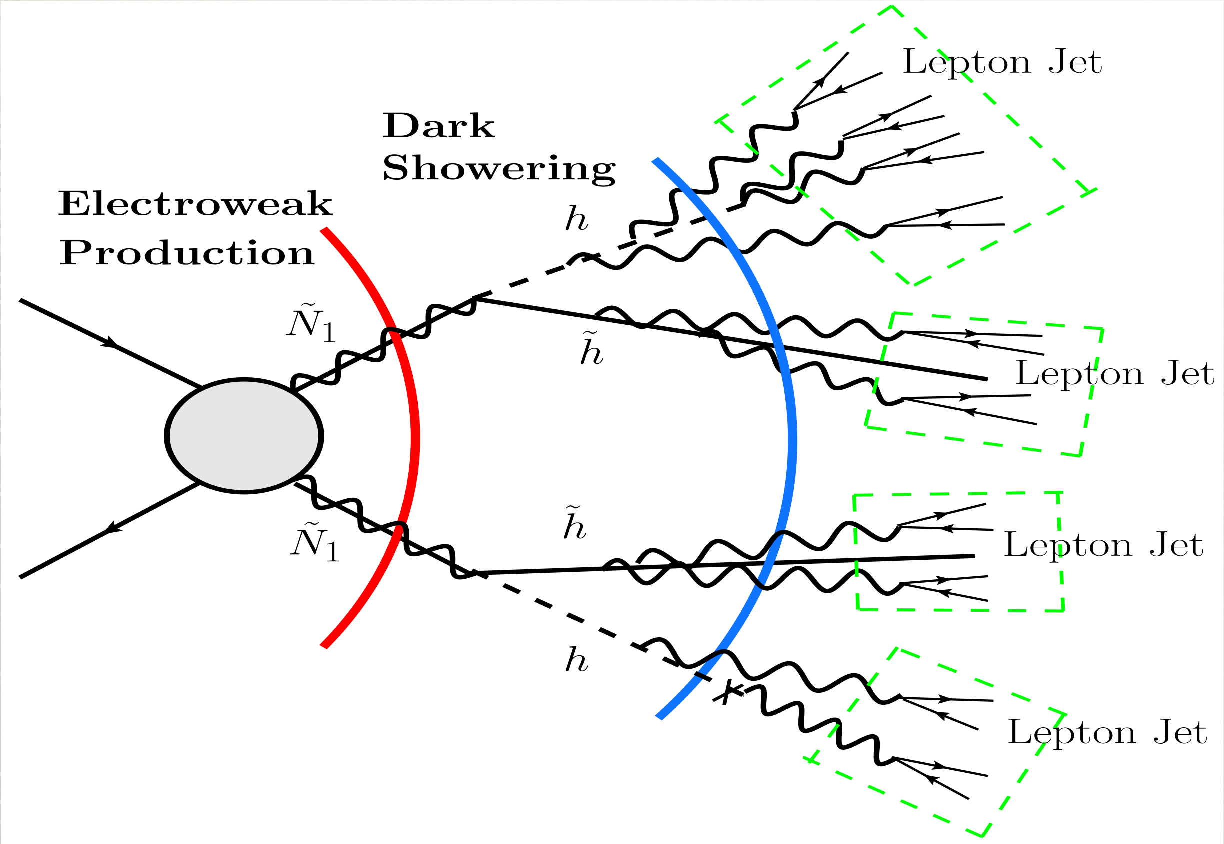


- Dark Matter explanations of Pamela anomaly → another example of overcoming the energy barrier

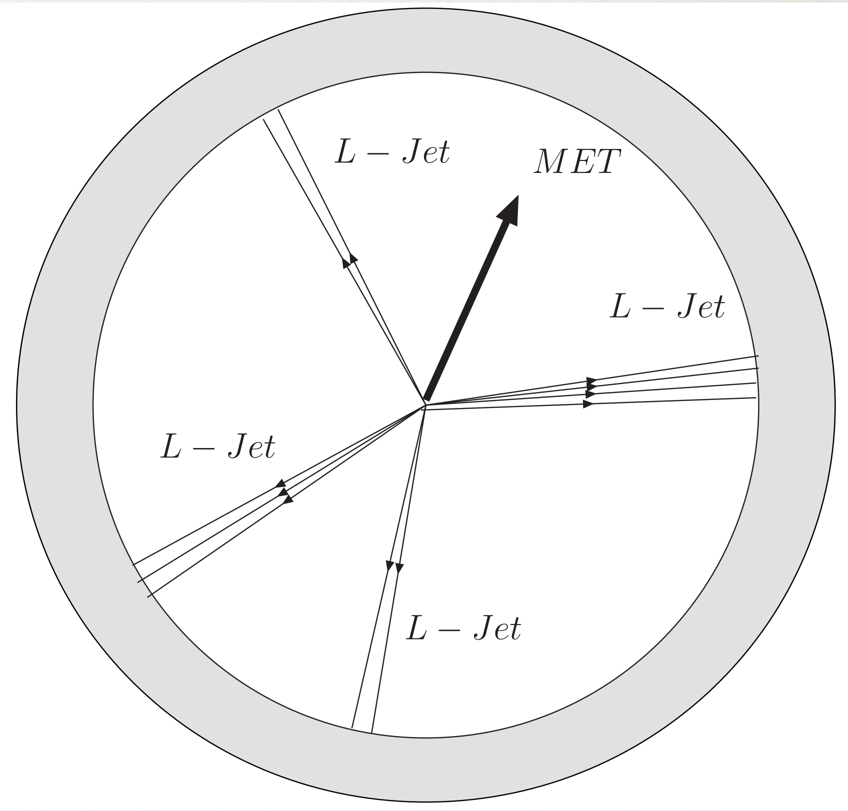
Hidden Valleys & Co.

- DM models spurred new interesting signatures at colliders

(DM too heavy to be produced, but other particles can couple with the light hidden sector…)



(Cheung et al.)

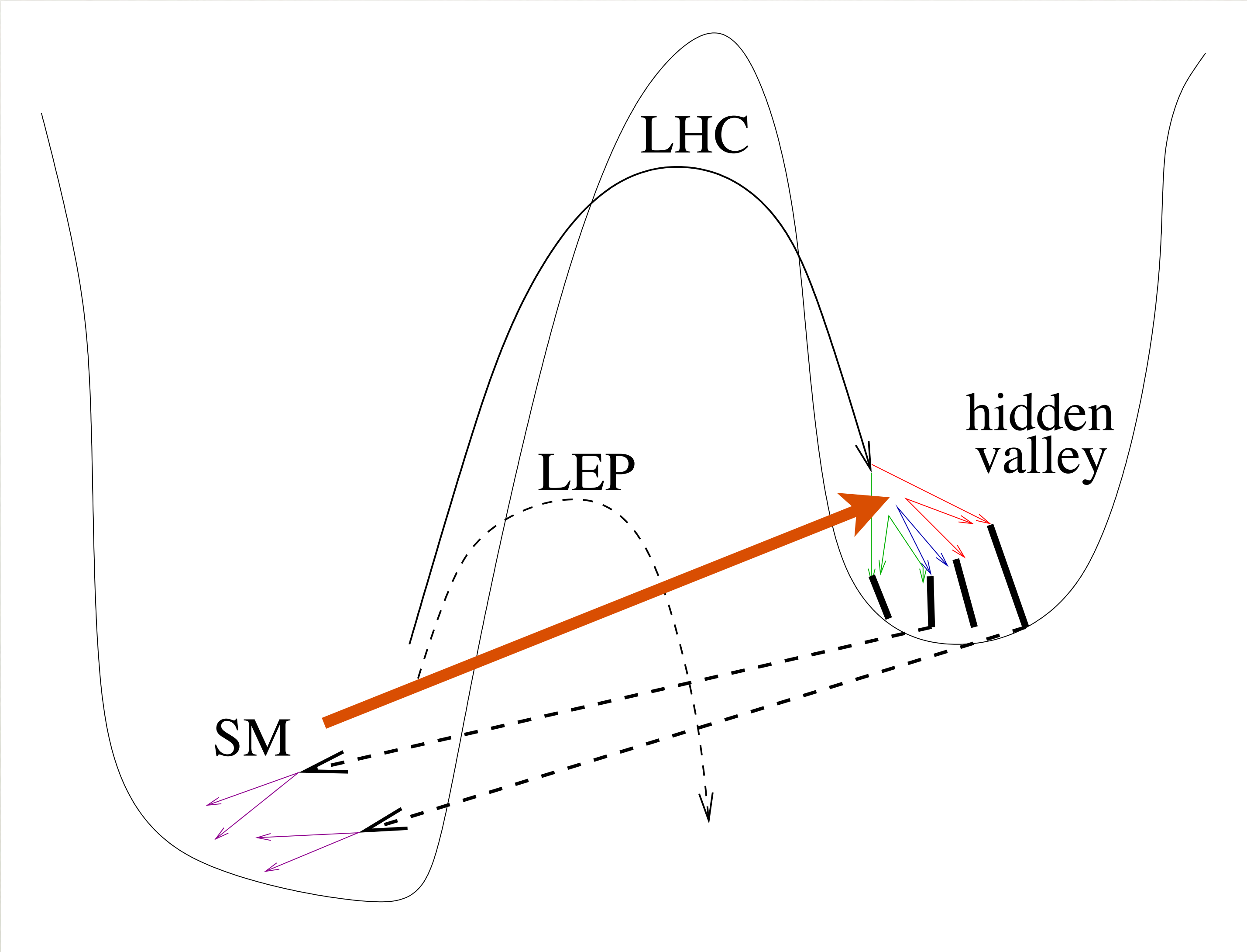


(Baumgart et al.)

Decays of hidden particles → Collimated pairs/groups of leptons (Lepton-jets)

Hidden Valleys & Co.

More direct probe: piercing the barrier!!

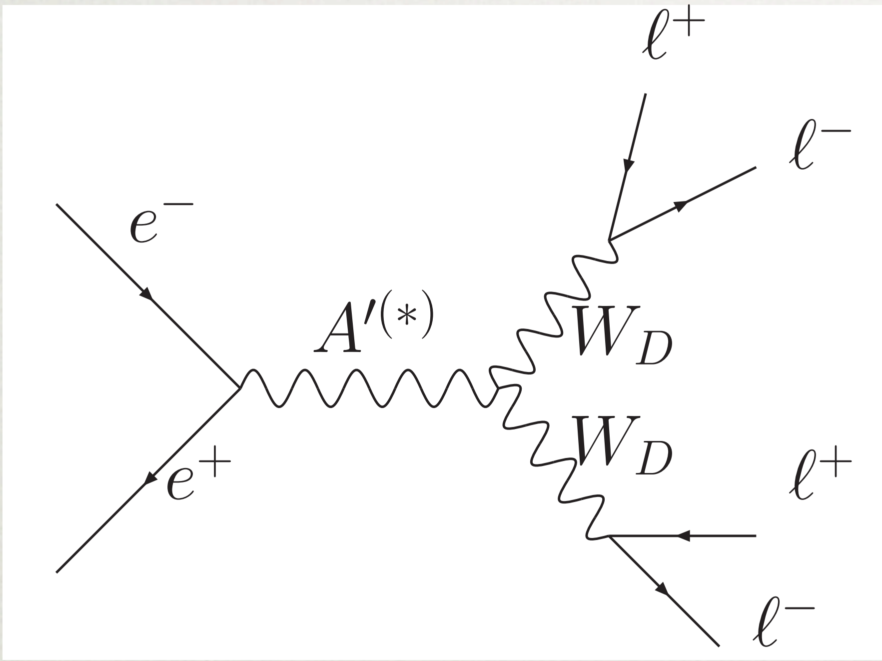


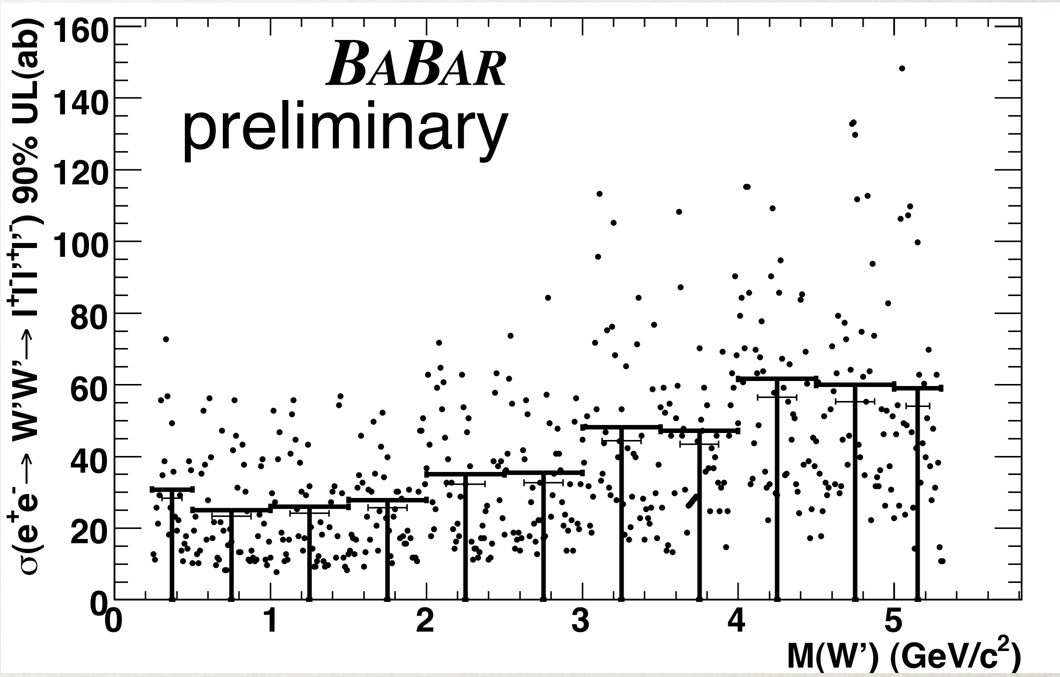
Low Energy & High luminosity experiments

High Luminosity Probes

- Searches at B factories:

(but also meson decays, ...)



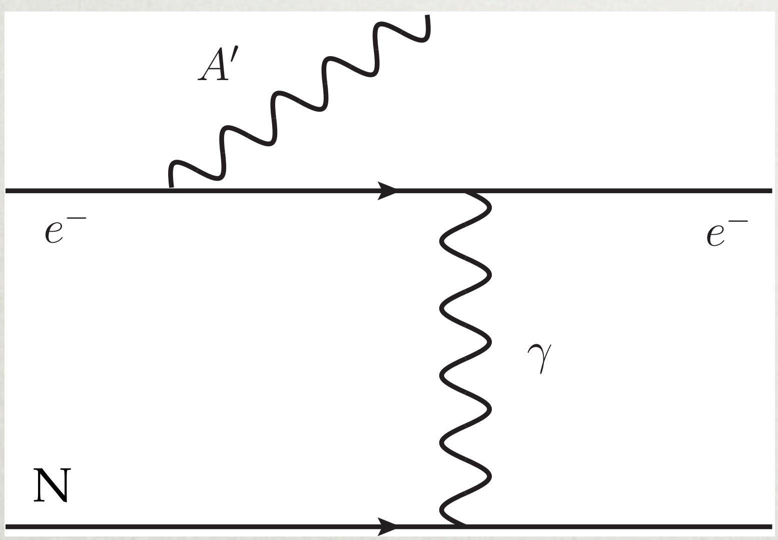


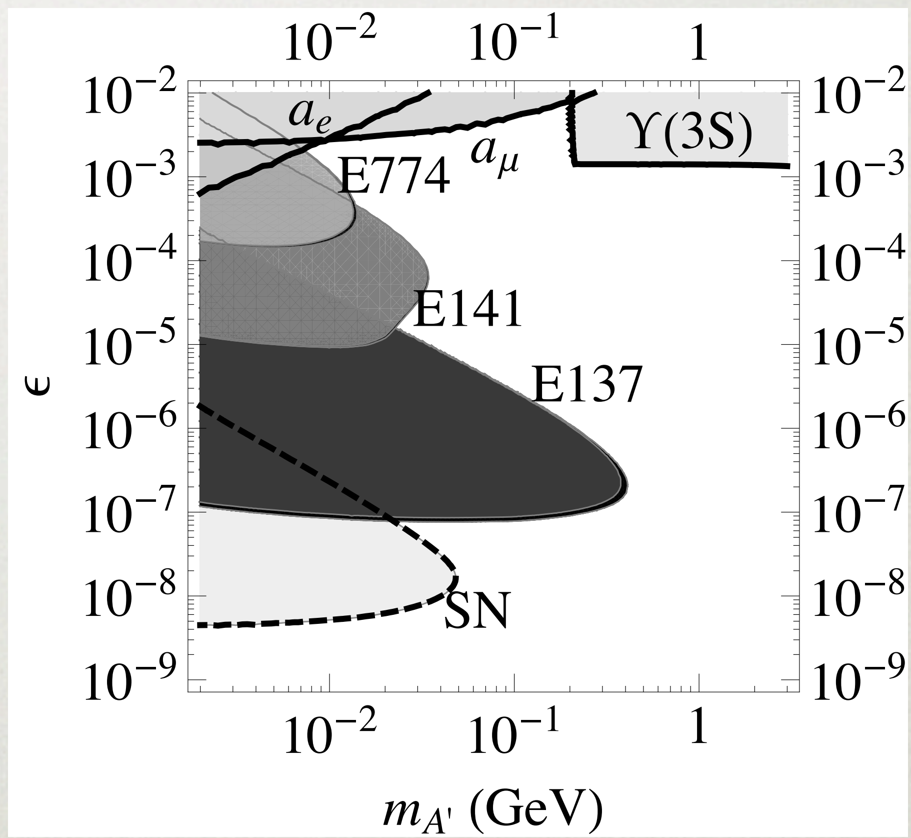
High Luminosity Probes

- Searches at B factories:

(but also meson decays, …)

- Past beam dump experiments:





(Bjorken et al.)

High Luminosity Probes

- Searches at B factories:

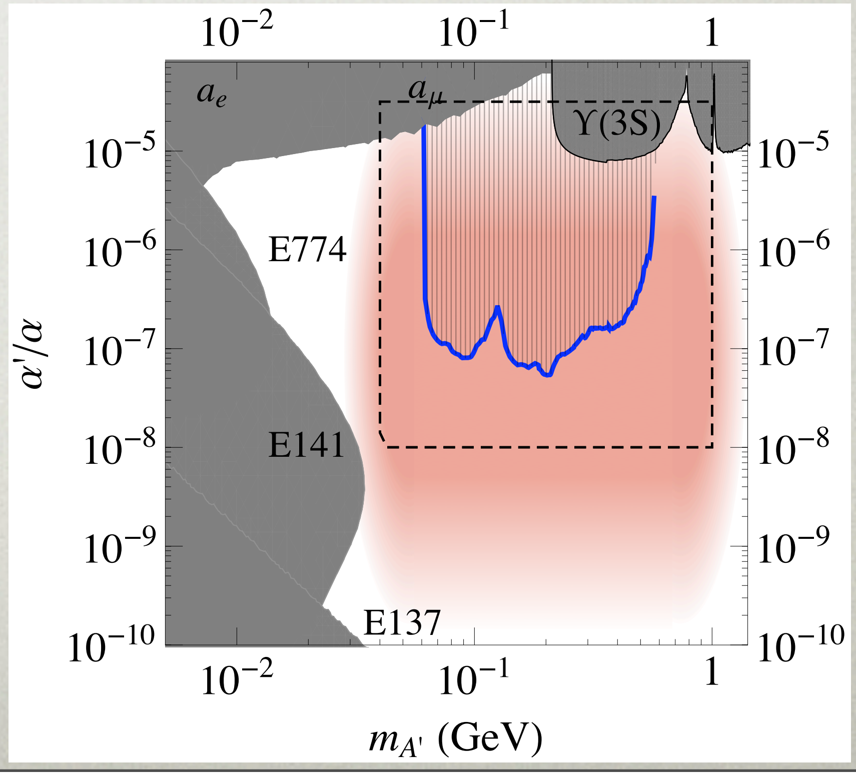
  (but also meson decays, ...)

- Past beam dump experiments:

- New beam dump experiments

e.g. APEX exp' @ JLAB

(Essig et al.)



Long Lifetimes?

- If hidden sectors very weakly coupled particles can get quite long lived pretty easily

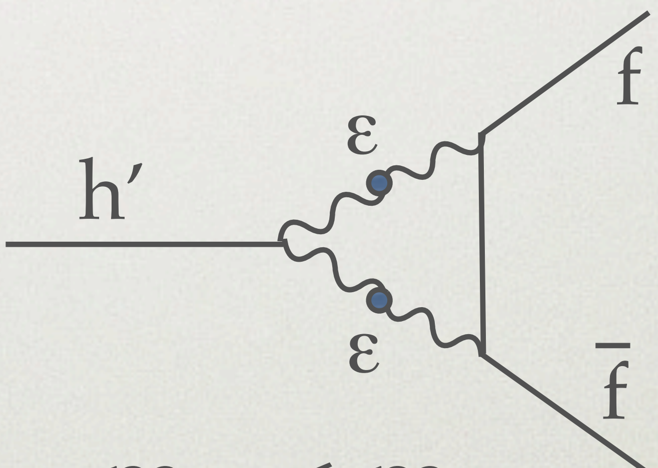
Long Lifetimes?

- If hidden sectors very weakly coupled particles can get quite long lived pretty easily

Vector portal:

$$\Gamma_{h'} \propto \frac{\alpha\alpha'}{16\pi^2}\epsilon^4 m_{h'} \left(\frac{m_f}{m_\phi}\right)^2$$

Massive spin-1 ϕ that mixes with photon
$\rightarrow$ hidden "Higgs" h′ @ GeV



$m_{h'} < m_\phi$

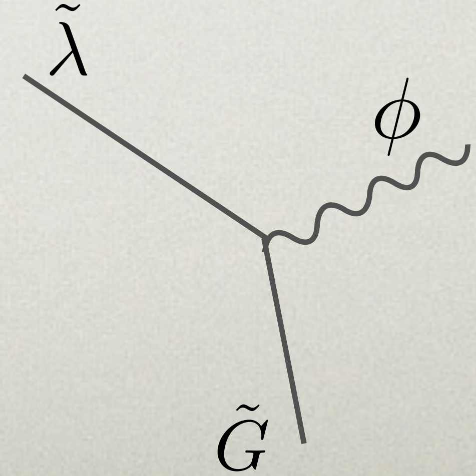
Long Lifetimes?

- If hidden sectors very weakly coupled particles can get quite long lived pretty easily

Vector portal: $$\Gamma_{h'} \propto \frac{\alpha\alpha'}{16\pi^2}\epsilon^4 m_{h'} \left(\frac{m_f}{m_\phi}\right)^2$$

SUSY hidden sector: $$\Gamma \propto \frac{m_{\tilde{\lambda}}}{16\pi} \left(\frac{m_{\tilde{\lambda}}^2}{F}\right)^2$$

(need to stabilize the ~1 GeV scale…)



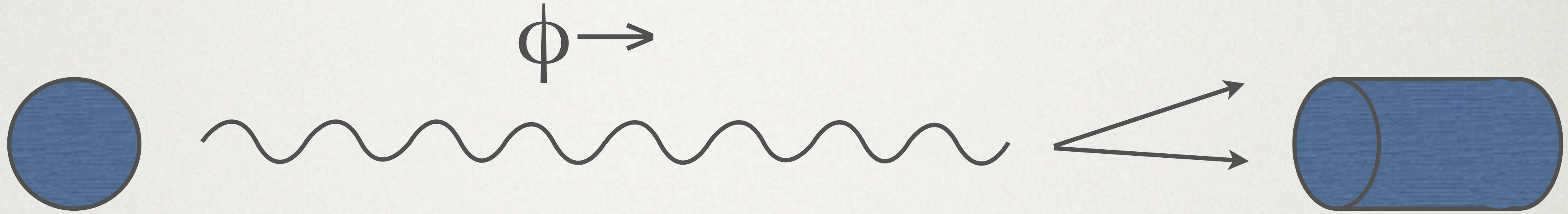
Lightest Hidden SUSY Particle may decay into gravitino

Long Lifetimes?

- If hidden sectors very weakly coupled particles can get quite long lived pretty easily
- Some constraints from Cosmology (BBN) but often can be evaded (shouldn't prevent an experimental search)
- In some cases covered by beam-dump experiments
- Worth exploring all possibilities to probe different lifetimes (and mass scales)...

Looking for Long Lived Particles (LoLiPs)

(Batell et al.; Schuster et al.; Meade et al.)

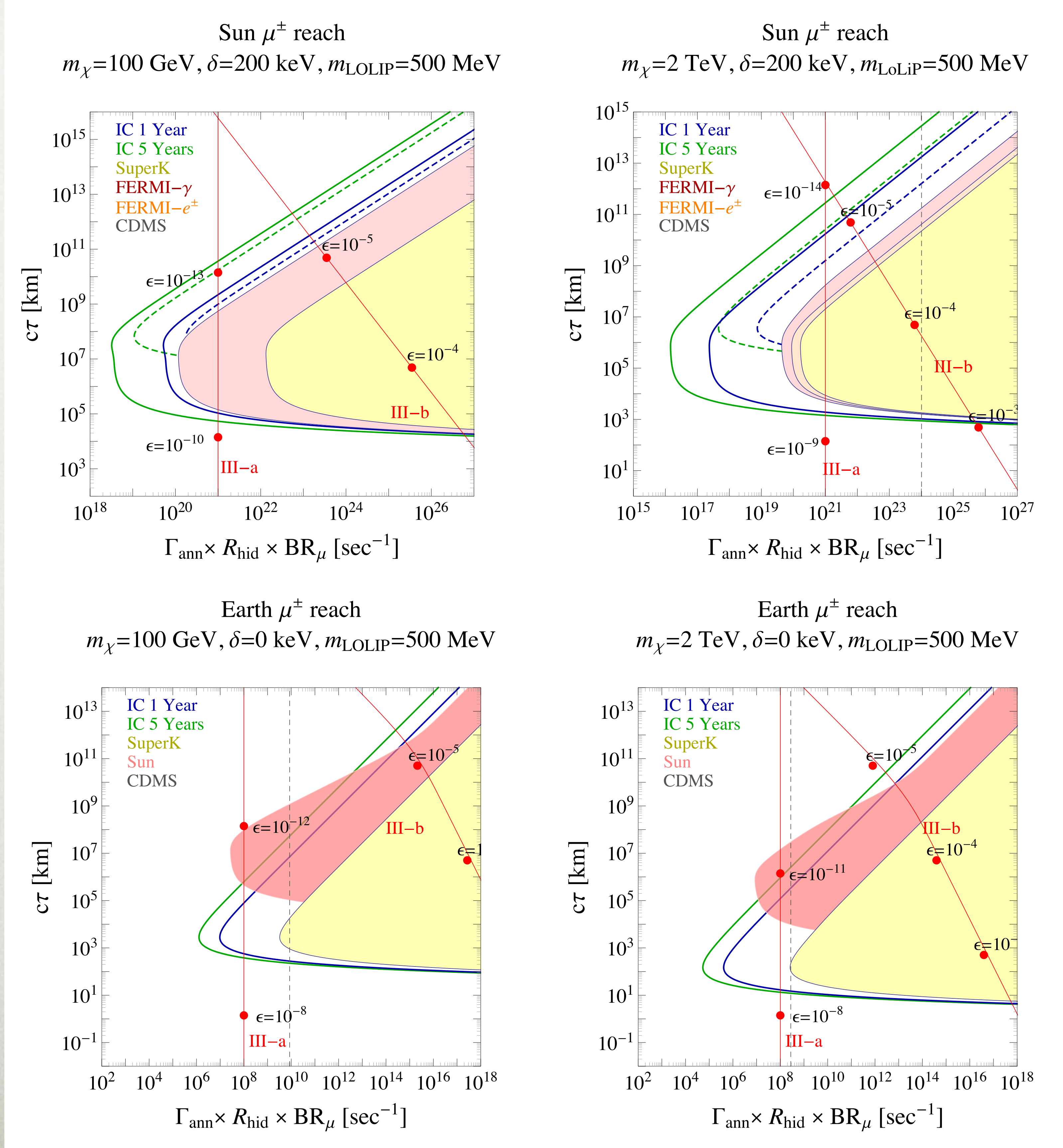


DM DM $\rightarrow \phi\ \phi$ $\qquad$ $\phi \rightarrow$ SM SM

- Nearby sources of DM annihilations: center of the Sun and the Earth
- Relevant detectors: SuperK, Fermi, IceCube
- May probe wide range of lifetimes: $10^2\text{km} \leq c\tau \leq 10^{12}\text{km}$

Looking for Long Lived Particles (LoLiPs)

- Strong limits from Fermi γ and e± (decays in-flight from the Sun)
- IceCUBE ν telescope can improve the bounds (no new experim, just new analysis...)



Conclusions

- DM annihilations or decays is still a viable explanation for PAMELA & FERMI results
  - Annihilations/decay into many $(e^{\pm})$, $\mu^{\pm}$, $\pi^{\pm}$ and high DM mass (~2-5TeV) are required
  - τ's final states are now excluded both for annihilating and decaying
- Presence of a hidden sector (hinted by DM) may show up in other places → explore ways to detect it (colliders, ν telescopes, beam dumps, ...)

Backup slides

Dark Matter Profile

- Dark Matter Profile inferred from N-body simulations
- Current hi-res simulations have resolutions of O(0.1 kpc)
- Best fit is for Einasto profile: $\rho(r) = \rho_\odot \exp\left[\frac{-2}{\alpha}\left(\left(\frac{r}{r_s}\right)^\alpha - 1\right)\right]$

- α=0.12-0.2, here 0.17
- No baryonic components in the simulations: may drastically change the results!
- Study also a cored IsoThermal as a shallower profile